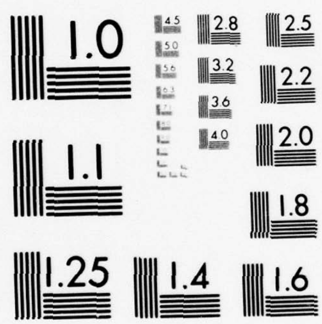
AD-A062 751 SOUTHWEST RESEARCH INST SAN ANTONIO TEX DEPT OF ENGIN--ETC F/G 21/4
SINGLE-CYLINDER DIESEL ENGINE TESTS WITH UNSTABILIZED WATER-IN---ETC(U)
AUG 78 J O STORMENT, C W COON DOT-TSC-920

UNCLASSIFIED USCG-D-13-78 NL

1 OF 1
AD
A062751

END
DATE
FILMED
3-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

REPORT NO. CG-D-13-78

LEVEL II

12

SINGLE-CYLINDER DIESEL ENGINE TESTS WITH UNSTABILIZED WATER-IN-FUEL EMULSIONS

J.O. Storment
C.W. Coon

Southwest Research Institute
San Antonio TX 78284

AUGUST 1978

FINAL REPORT

THIS DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE DEFENSE DOCUMENTATION CENTER, CAMERON STATION, ALEXANDRIA VA 22314

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
U.S. COAST GUARD
Office of Research and Development
Washington DC 20590

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

(19) (18) USCG, TSC

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-13-78, USCG-77-4		

4. Title and Subtitle
(6) SINGLE-CYLINDER DIESEL ENGINE TESTS WITH UNSTABILIZED WATER-IN-FUEL EMULSIONS.

5. Report Date
(11) August 1978

6. Performing Organization Code
AR-1206

7. Author(s)
(10) J. O. Storment and C. W. Coon

8. Performing Organization Report No.
DOT-TSC-USCG-77-4

9. Performing Organization Name and Address
Southwest Research Institute*
6220 Culebra Road
Department of Engine and Vehicle Research
San Antonio, Texas 78284

10. Work Unit No.
CG807/R8005

11. Contract or Grant No.
(15) DOT-TSC-920

12. Sponsoring Agency Name and Address
(12) 87p.

13. Type of Report and Period Covered
(9) Final Report.
Jan. 1977 - June 1977

14. Sponsoring Agency Code

15. Supplementary Notes
*Under contract to: U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge, Massachusetts 02142

16. Abstract

A single-cylinder, four-stroke cycle diesel engine was operated on unstabilized water-in-fuel emulsions. Two prototype devices were used to produce the emulsions on-line with the engine. More than 350 test points were run with baseline diesel fuel and emulsified water-in-fuel. Water content of the emulsified fuel varied from about 2% to 23% by volume. Statistically significant decreases in fuel consumption, ranging from 1.2% to 5.1% were obtained with emulsified fuels in 20 out of 36 test conditions. An increase of 2.5% was measured at one condition only. Use of the emulsified fuels decreased oxides of nitrogen by up to about 60% and Bosch smoke numbers by up to almost 70%, whereas unburned hydrocarbons increased up to over 130%. Carbon monoxide changes with emulsified fuel varied from a decrease of 52% to an increase of over 170%, depending on engine speed and power, and water content of the fuel. No problems were encountered in engine operation at any test condition with the water-in-fuel emulsions.

17. Key Words
Diesel Engines
Water-Fuel Emulsions
Diesel Emissions
Diesel Fuel Consumption

18. Distribution Statement
This document is available to the public through the Defense Documentation Center, Cameron Station, Alexandria VA 22314

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	91	

Form DOT F 1700.7 (8-69)

410 094 78 12 26 113

PREFACE

This work was performed for the Department of Transportation, United States Coast Guard, Office of Research and Development, under a contract issued by the DOT Transportation Systems Center. The technical monitors for the Coast Guard were James White and Fred Weidner; for TSC, Robert Walter. The efforts of John Cavanaugh and Donald Taylor of Daedalean Associates, as well as Raymond Thompson and Albert Constantine of Dynatrol Ltd., assured the successful completion of these tests. Rodney Bauer of the Department of Engine and Vehicle Research, Southwest Research Institute, conducted the tests.

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

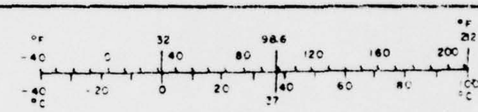


TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

SPONSOR'S FOREWORD

Our primary purpose in sponsoring this research was to establish whether or not water-in-fuel emulsion would reduce fuel consumption of a diesel engine. This has been accomplished for the single-cylinder laboratory engine tested here. However, at present, there is no established scientific basis for obtaining these savings. It was hoped that some insight would be gained by recording engine cylinder pressure-time profiles and the rate of heat release. However, the pressure profiles indicated little, if any, change with use of the emulsions (see Section 3.9) and instrumentation problems were encountered in measuring the rate-of-heat release. In any case, it is evident that tests of an even more fundamental nature should be performed.

It was not our purpose to compare either the performance of the two emulsification devices tested here or the emulsions produced by them. Such a comparison would be invalid for the following reasons:

1. The devices were not specifically designed for use with the test engine.
2. The emulsions from each device were introduced at a different point in the engine fuel system.
3. A different test matrix was used for each emulsor tested.

The test matrix used with the Dynatrol emulsor reflected, in part, the advice of Raymond Thompson of Dynatrol Ltd. His experience indicated that a low water content was more effective at low engine power conditions.

1. INTRODUCTION

1.1 Background

The current emphasis on energy conservation has precipitated the investigation of a number of devices and techniques oriented toward fuel savings. There is presently a high level of interest, particularly among large users of liquid fuels, in system modifications or fuel additives that can diminish fuel requirements or extend available fuel supplies.

Among the suggestions that have been made in the interest of fuel conservation is the recommendation that water be added to liquid engine fuels as a means of enhancing combustion properties and extending supplies. Water addition has received dramatic coverage in the popular press, although some reports have been without basis in technical fact. A number of systems and devices have been announced, and enthusiastic claims have been made for their efficacy.

Performance claims which are obviously excessive or thermodynamically unsound can generally be recognized and disregarded; however, there are also reports and data from reliable investigators that indicate some advantage as a result of the addition of water to fuel. Most notably, the use of water-in-fuel emulsions (i.e., the fuel forms the continuous phase, the water the discontinuous phase) has been associated with significant reductions in the emission of smoke and/or oxides of nitrogen from continuous burners, such as those used in turbine engines(1)*, furnaces and boilers(2). The available results also indicate that similar advantages may be obtained through use of fuel-water emulsions in internal combustion engines(3,4).

The basic mechanism which is postulated for combustion of fuel-water emulsions is the presence of "micro-explosions". It is believed that a droplet of emulsion occurring in the spray from a fuel nozzle contains a number of discrete globules of water surrounded by fuel. When the droplet is heated, the water remains in the liquid state until a temperature far above the boiling point is attained. The transition to the vapor phase occurs quite rapidly and violently, and the fuel droplet is divided or shattered into smaller entities (so-called secondary atomization). The result of this process in an engine cylinder would be improved mixing of fuel and air, with resulting improved combustion. The micro-explosion phenomenon has been demonstrated in laboratory experiments(5), and basic theoretical research efforts(6) are presently underway that will define the nature of the emulsions that will yield maximum mixing effects under engine operating conditions.

In the absence of this basic data, the studies on various combustion systems must be considered. These experiments are in some degree lacking, since all of the pertinent variables have not been defined, and all of the

---

*Numbers in parentheses designate References at end of report.

interactions between the fuel and the combustion process are not yet known. The basic studies will not be complete for several years; however, the need for improved fuel economy is current, and it is therefore necessary to undertake practical experiments that will define the benefits and drawbacks arising from use of emulsified fuel and, perhaps, lead to a basic definition of desirable fuel-water emulsion properties. Subsequent results from the more scientific programs may indicate superior alternatives in these properties which can be utilized as they become known and available. However, such benefits as are presently available should be incorporated into fuel combustion processes as soon as possible.

Considerable discussion has been devoted to the relative merits of stabilized and unstabilized emulsions. Stabilized fluids utilize surfactant (surface-active) compounds to isolate the fuel and water so that the resulting emulsion can be stored for relatively long periods. Unstabilized emulsions are simple dispersions of water and fuel, and they begin to separate (deemulsify) within seconds after mixing occurs. The implications of emulsion stabilization are not clearly defined in the area of combustion and fuel economy improvement; however, for large mobile sources there are clear disadvantages to the use of additional stabilizing fluids during the formulation of the emulsions. Furthermore, unstabilized emulsions seem to offer fuel economy advantages that have not been consistently observed in engine tests with stabilized emulsions[7,8,9].

All of the potential benefits associated with use of fuel-water emulsions attracted the attention of the United States Coast Guard. Since the Coast Guard fleet consumes large quantities of diesel fuel, it would be desirable to make use of any system or technique which would enhance fuel economy. Accordingly, a program was initiated with Daedalean Associates, Inc. that would lead to the design and development of a fuel-water emulsification system. As this project neared an end, engine test facilities were required for the assessment of the effects that might be expected, and Southwest Research Institute (SwRI) was asked to conduct a test program that would define the engine performance aspects of the fuel-water emulsion delivered by the Daedalean system.

After the program at SwRI had attained the advanced planning stages, another fuel-water emulsification system came to the attention of the Coast Guard. The Dynatrol system was developed by Professor Ray Thompson of the University of Newcastle upon Tyne. The developer claimed that emulsions of superior quality could be produced with a small device using relatively small amounts of power. It was decided that a prototype unit of this device should be included in the testing program at SwRI.

1.2 Objectives

The primary objective of the effort described in this report was the performance of a brief, but thorough, test program that would define the possible benefits associated with the use of fuel-water emulsions in diesel engines. Tests were conducted using a single-cylinder research engine in order to

determine the advisability of pursuing both the testing program with large-scale engines and a development program for enhanced fuel-water emulsification capability.

It should be noted that comparison of these particular emulsification devices was specifically not an objective of this program. Both of the systems supplied to the Institute were thoroughly protected by non-disclosure agreements, and neither Institute nor Government personnel were allowed to examine the internal components of the emulsifiers. Instead, the testing program was oriented toward evaluation of the possible benefits that might result from the use of the products supplied by the two emulsification systems. Specific comparisons between systems should be made only after systems are available for complete examination and after test data are obtained from the engines that the devices will serve in the field.

1.3 Approach

The approach utilized by Institute investigators in this study can best be characterized as direct rather than basic. No attempt was made to optimize emulsion characteristics or to investigate specific relationships between fuel-water emulsions and the combustion process. Instead, a single-cylinder engine was operated using both conventional diesel fuel and emulsions generated by the two emulsification systems supplied by the Coast Guard. In all cases, the emulsions were of the unstabilized type; no surfactants were added to prolong the lifetime of the fuel-water mixture. Both of the emulsification systems were attended by the developers or their representatives during most of the tests.

In order to determine whether a potential advantage existed for the use of emulsions in Coast Guard vessels, tests were conducted using a single-cylinder research engine equipped with comprehensive instrumentation, and detailed measurements of fuel consumption and engine operating parameters were made. The sequence of test runs was constructed in such a way that individual tests with emulsions were immediately preceded by tests with conventional diesel fuel at the same engine condition. Using this technique, baseline data were acquired concurrent with the data on the test fuel, and reliance on previously executed baseline information was unnecessary. The tests at each test condition were repeated from four to six times, and statistical tests were applied to the fuel consumption data in order to define the confidence level associated with any observed changes in the numerical values.

During the period of performance of the engine tests, the quality of the fuel-water emulsion generated by each system was monitored by representatives of the Transportation Systems Center and the United States Coast Guard. Samples were drawn of the emulsion that was supplied to the engine, and data were obtained by photographing the emulsion through an optical microscope, by allowing the samples to settle in a graduate, and by centrifuging a sample to

achieve total water removal from the fuel. The results of this study of emulsion quality will be reported at a later date in a DOT/USCG report.

The results obtained from the engine test program offer a reasonable estimate of the magnitude of the fuel economy benefit that might be obtained by the use of fuel-water emulsions in diesel engines. In addition, the implications of emulsion use in the area of engine performance and emissions can be inferred from the data. While the advantages defined by the present program reflect the current state of knowledge, it is probable that full utilization of emulsion benefits will require a considerable additional effort devoted to optimization of emulsion quality and modification of the combustion system. These efforts are proceeding in a number of laboratories, and it is hoped that the information reported herein will be of benefit to other investigators for the calibration of mathematical models and the definition of emulsion characteristics.

2. EXPERIMENTAL APPARATUS AND TECHNIQUES

The study of fuel-water emulsions was performed using a single-cylinder laboratory test engine as the primary analytical tool. Although wide use of emulsions in single-cylinder engines is not likely, the laboratory engine does offer the opportunity for excellent control of an experiment, and it allows the application of a broad range of instruments for the determination of fuel-dependent parameters. Furthermore, definitive tests can be conducted with small quantities of fuel that would be completely inappropriate for large-scale engine tests. Single-cylinder engine experiments are widely used throughout the research and development community as a means of assessing the significance of changes in fuels, lubricants, and engine hardware.

2.1 Equipment

The test engine used in this program was manufactured by the Laboratory Equipment Company (Figure 2.1). The bore and stroke are 3.8125 and 3.750 inches, respectively; the displacement is 42.8 cubic inches. The engine was equipped with a standard open-chamber diesel head and a "Mexican hat" piston. The compression ratio was 16.7:1. A 60 degree shroud was installed on the intake valve in order to produce the proper air swirl rate within the combustion chamber. The basic engine fuel system included a Bosch APE1B injection pump with an 8 mm barrel and plunger and a TMB variable timing assembly. Injection of fuel into the cylinder was accomplished with a Sims NL141 (4-hole) nozzle set to a valve opening pressure of 2150 psi. The intake valve was open from 18 degrees before top dead center to 58 degrees after bottom dead center, and the exhaust valve was open from 124 degrees after top dead center to 20 degrees after top dead center. Maximum lift for both valves was 0.228 inch. The engine assembly included a massive flywheel and a system of rotating counterweights to provide smooth operation over the speed range.

The engine was connected to a cradled dry-gap, eddy-current dynamometer capable of absorbing 30 hp. The engine-dynamometer assembly was connected through a clutch to a 20 hp electric motor which was utilized for engine starting and measurement of motored engine friction at any speed up to 2500 rpm (Figure 2.2).

Engine speed was determined through the use of a magnetic pickup and a 60-tooth gear installed in the engine-dynamometer coupling. The speed signal was transmitted to a digital counter used as an output device. In addition, the signal from the magnetic pickup was supplied to a Digalog dynamometer controller capable of maintaining engine speed to plus or minus one rpm. Engine load was varied through adjustment of the fuel delivery rate, and measurement of the load was effected by observation of the force transmitted between the cradled dynamometer and a BLH load cell. The bridge circuitry for the load cell allowed determination of the beam load to within 0.1 lb.

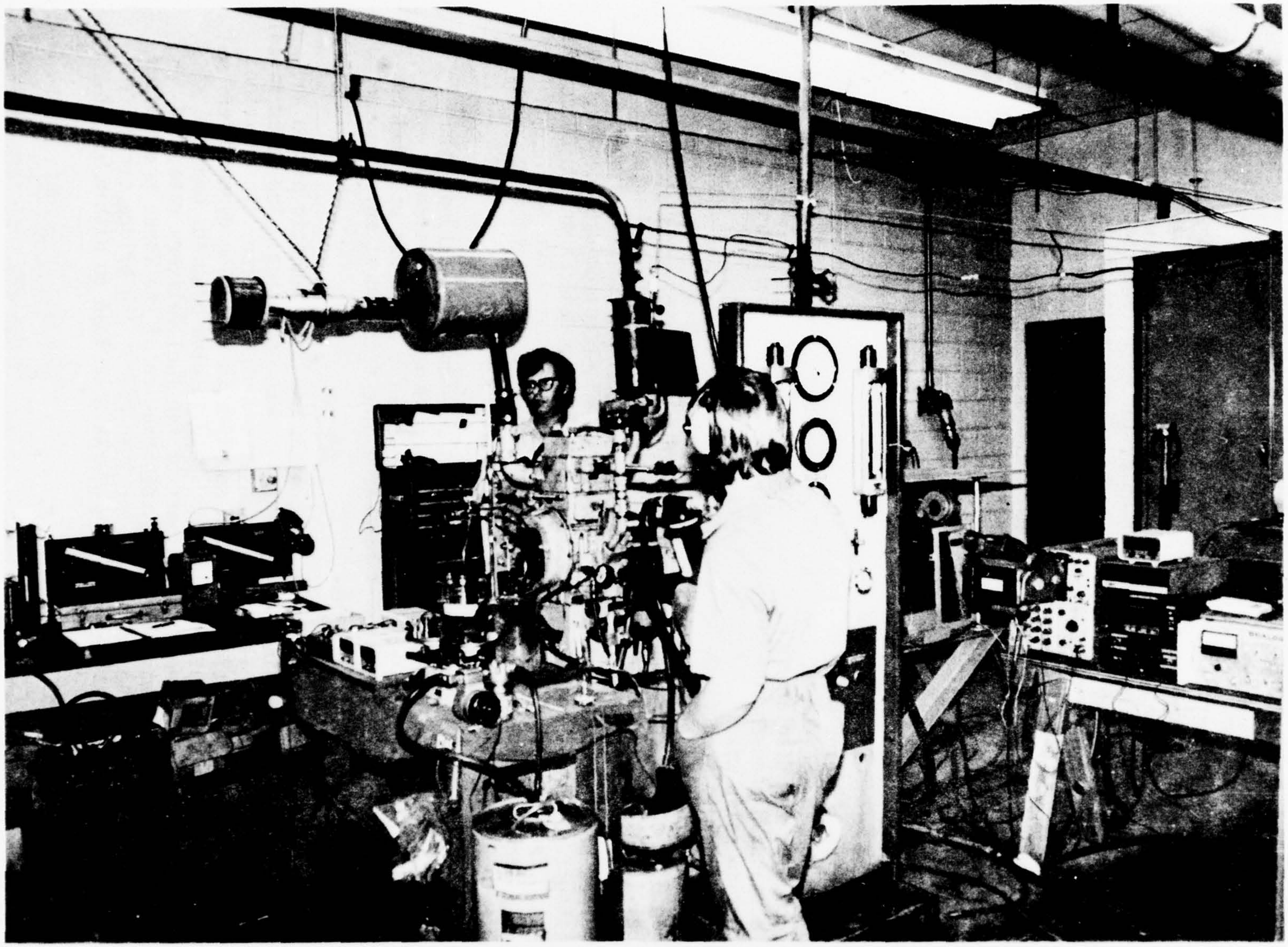


FIGURE 2.1 - SINGLE CYLINDER DIESEL ENGINE AND RELATED TEST EQUIPMENT

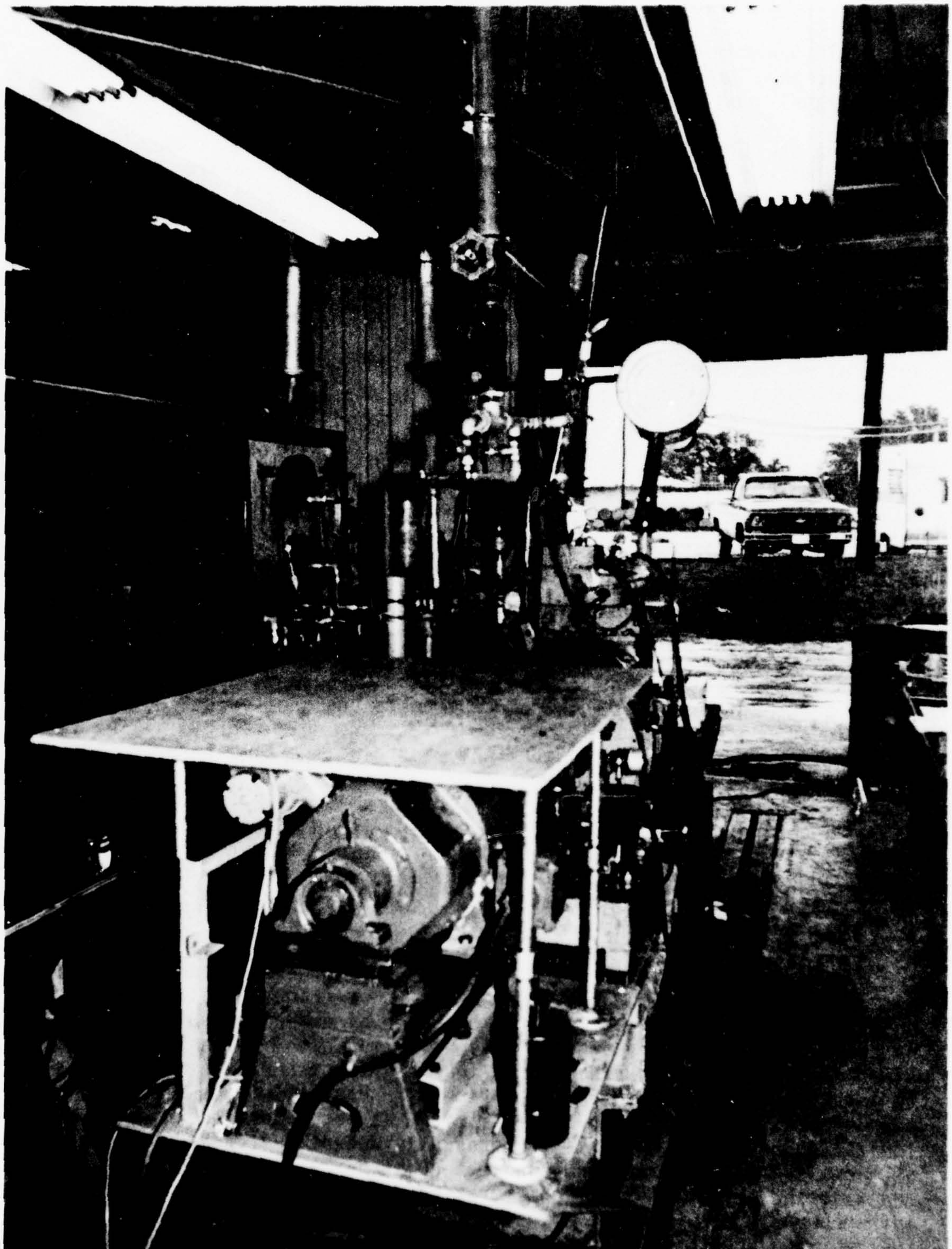


FIGURE 2.2 - REAR VIEW OF TEST ENGINE AND MOTORING DYNAMOMETER

Temperatures were recorded for the coolant inlet, coolant outlet, oil sump, the fuel at the pump and at the flowmeter, inlet air at both the engine intake and the flowmeter, engine exhaust and ambient air.

An oscilloscope was used to display cylinder pressure obtained from a piezoelectric transducer, injector needle lift obtained from an optical occlusion device, and timing marks obtained by means of a magnetic pickup and holes drilled in the engine flywheel.

Measurement of the engine inlet air flow was accomplished through the use of a laminar flow element. The pressure drops across the filter element and the measuring element were obtained using inclined water manometers. Atmospheric pressure was measured with a barometer, and temperature and pressure corrections were performed to reduce the observed flow rate to a standard condition.

The measurement of fuel flow rate was a critical element of the overall program. Following a brief initial evaluation of volumetric flowmeters, it was decided that direct observation of weight and volume flow rates would be most suitable for completion of the program objectives. Two fuel metering assemblies were constructed to accommodate the needs of the two emulsifiers used during the engine tests. The two systems had in common a graduated burette, a weight scale and a timing device. Schematic diagrams for both measurement systems are shown in Figures 2.3 and 2.4.

For experiments with the DAI emulsifier, diesel fuel measurements were made using both weight and volume techniques, and measured flow rates at the same engine condition were compared to one another during the data reduction process. The emulsion flow rates were obtained by filling the burette from the emulsifier output and recording the time required for consumption of a measured volume.

The Dynatrol emulsifier differed from the DAI unit in that it was located between the low pressure and high pressure elements of the fuel injection pump. Water flow rates were obtained through the use of a calibrated variable area flowmeter, and diesel fuel rates were obtained by both weight and volumetric techniques.

The gaseous emissions from the test engine were measured using instruments uniquely suited to each exhaust gas constituent (Figure 2.5). Since the unburned hydrocarbon emissions from diesel engines can be molecularly heavy by comparison with hydrocarbon emissions from a gasoline engine, the sample line between the engine exhaust and the instrument cart was maintained at a temperature in excess of 350 F to prevent condensation of the heavier compounds. The hydrocarbon concentration was obtained with a heated flame ionization detector, which is the presently accepted standard for measurement of hydrocarbon emissions from mobile sources using diesel engines. Carbon monoxide and carbon dioxide concentrations were determined using non-dispersive infrared analyzers. Oxides of nitrogen were measured using a chemiluminescent analyzer equipped with a converter capable of separating the contributions of NO and NO_x. The oxygen content of the exhaust stream was measured with a polarographic analyzer.

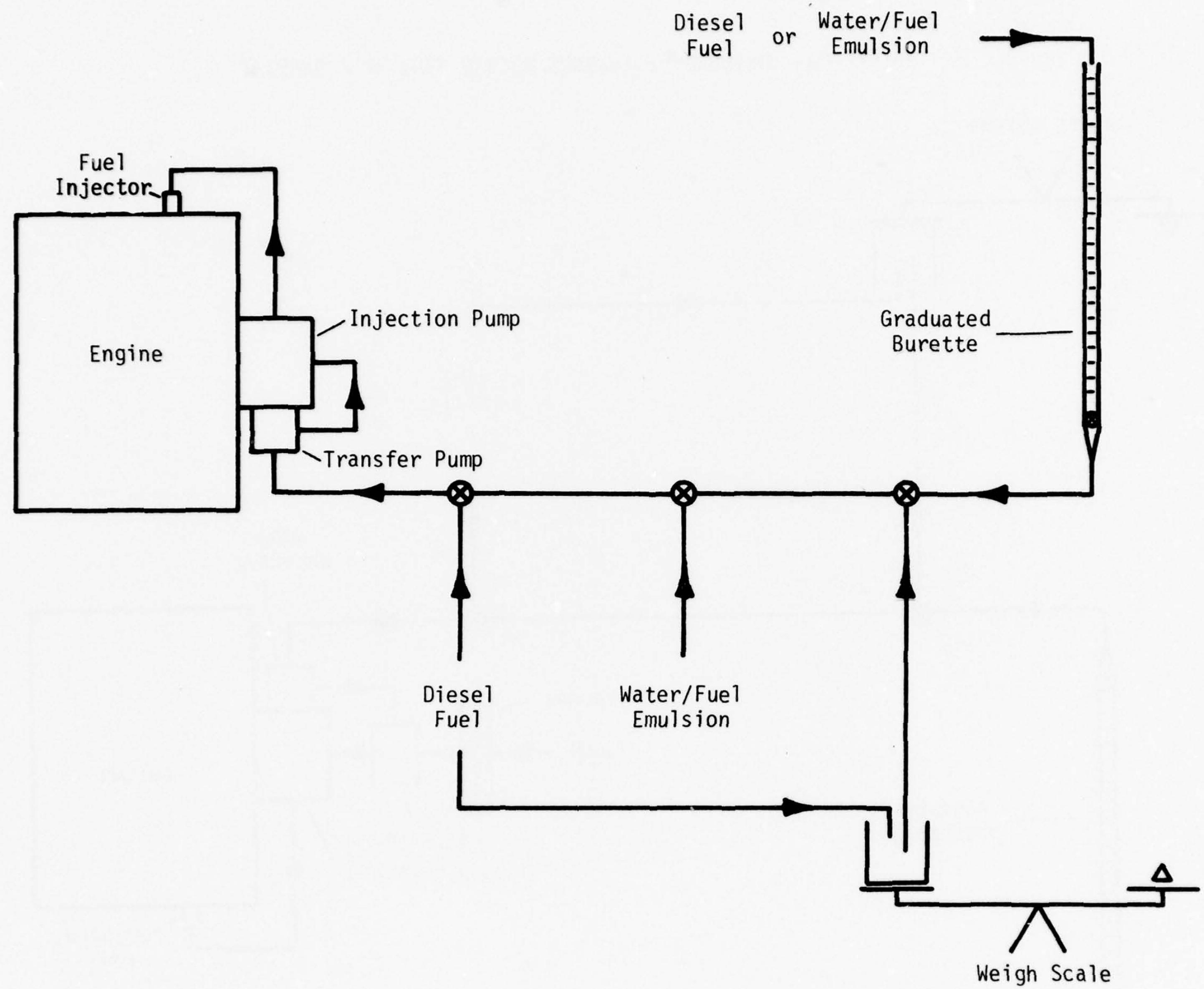


FIGURE 2.3- FUEL SYSTEM SCHEMATIC--DAEDALEAN EMULSIFIER

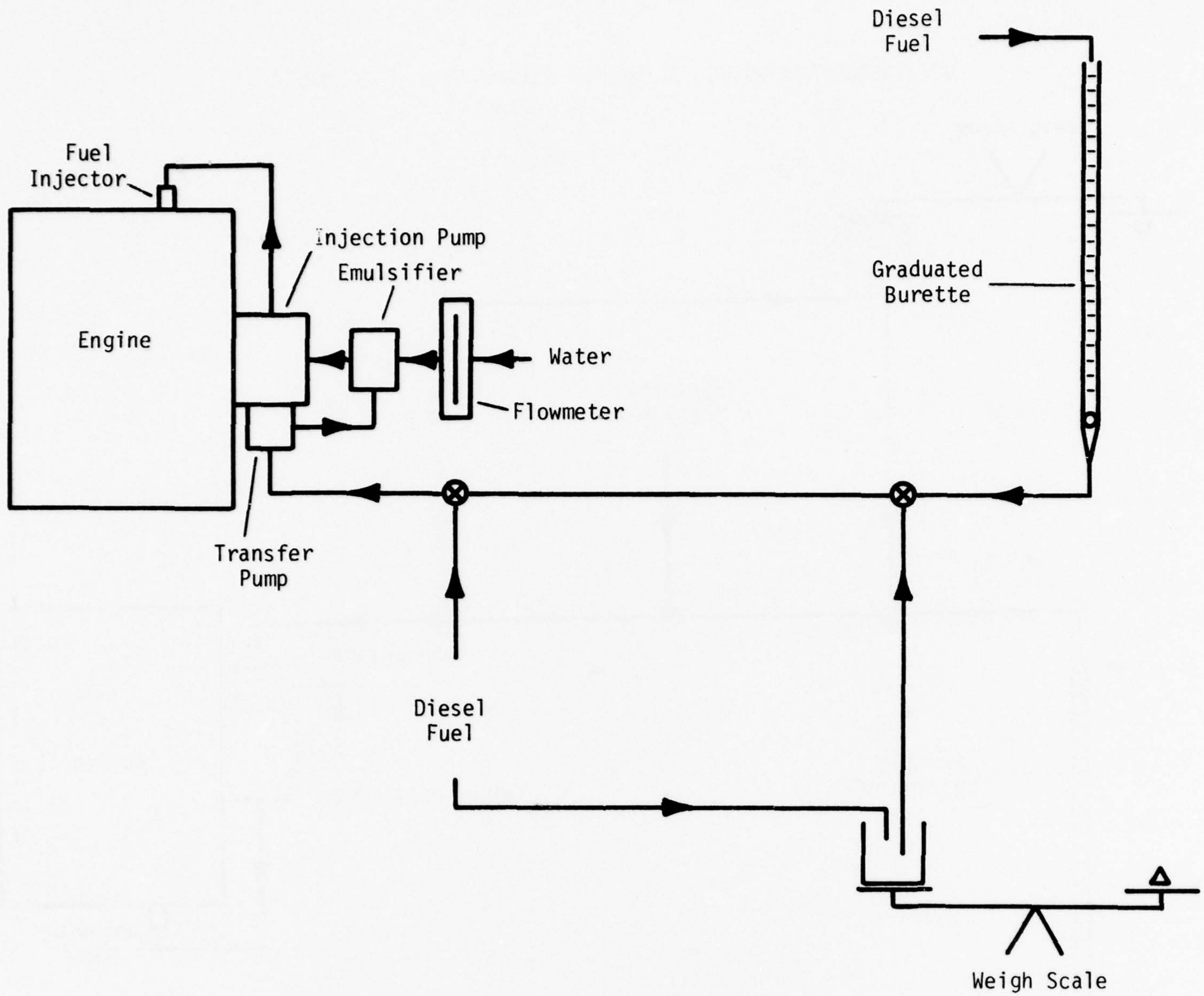


FIGURE 2.4- FUEL SYSTEM SCHEMATIC--DYNATROL EMULSIFIER

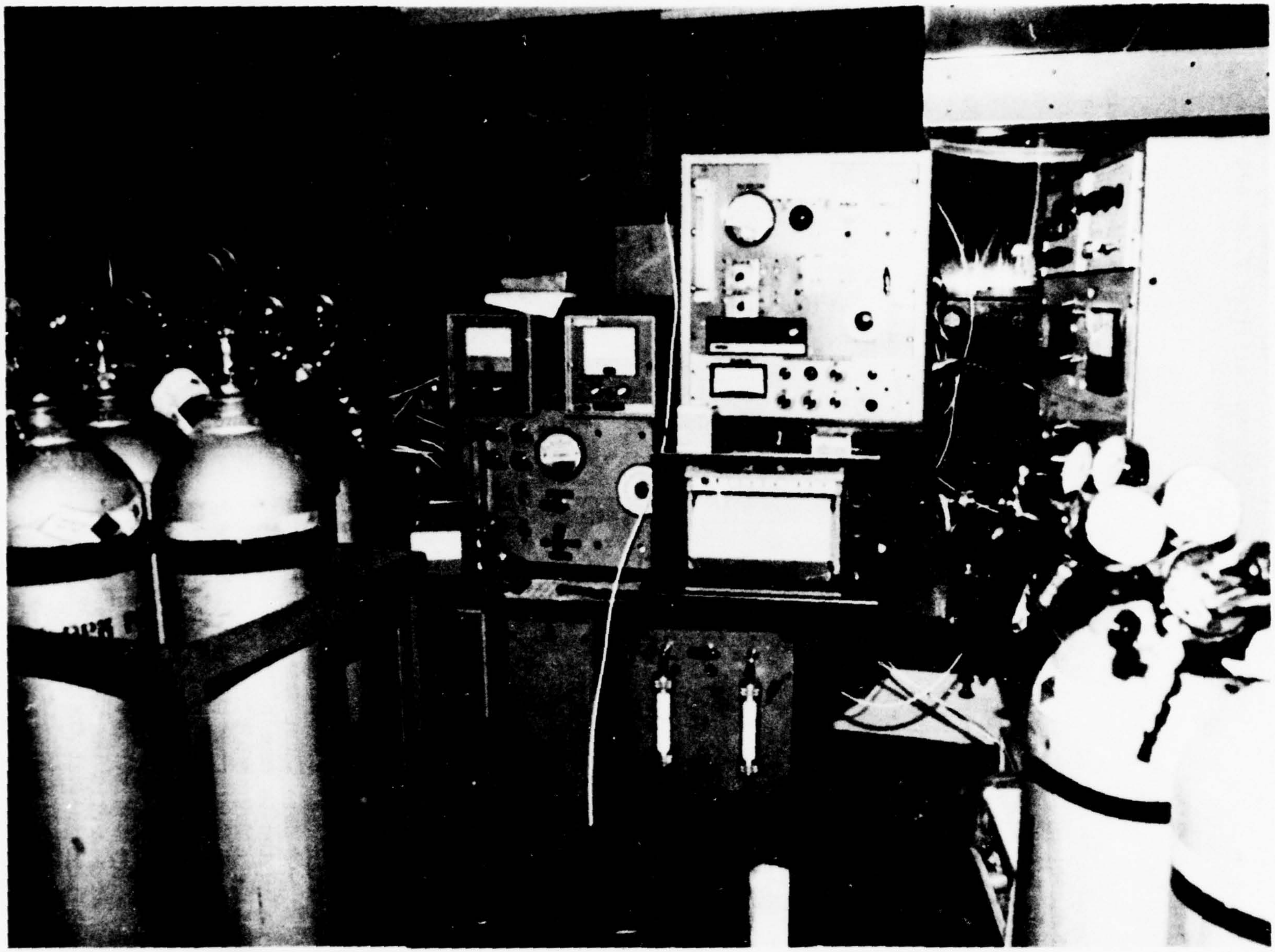


FIGURE 2.5 - GASEOUS EMISSIONS INSTRUMENTATION

Smoke density measurement of engine exhaust was obtained by a Bosch sampling apparatus. Sample spots were collected on filter paper and evaluated using the standard reflectance technique.

2.2 Run Procedure

In general, the test specifications and procedures employed in this program were guided by SAE J816b, the Engine Test Code for spark-ignition and diesel engines. This code is widely used by engine testing laboratories, and it serves as a convenient reference for instrument standards and procedures.

The basic test matrix consisted of six test points: speeds of 1000 and 2000 rpm and brake torque values of approximately 8, 12 and 16 lb-ft for each speed. A few tests were conducted at 2500 rpm and these torques. The test points were readily reproduced, and they allowed convenient comparison between the baseline fuels and the experimental fuels. All test conditions, including emulsion water contents, used in this program are given in Table 2.1.

At the start of each day of testing the engine was started and operated at relatively high load on diesel fuel until normal oil sump and coolant temperatures were obtained. The engine speed and load were then adjusted to the values desired for the first run condition. Fuel rate and injection timing were then adjusted iteratively until the timing associated with maximum brake torque was attained. A period of several minutes was then allowed for stabilization of operating conditions parameters.

When the operator was convinced of engine stability, the data specified on the test form were recorded. A photograph of the oscilloscope traces was obtained and attached to the data record for each run. The fuel system was then converted to allow engine operation using emulsified fuel, and another period was allowed for attainment of stable operating conditions. The injection timing and fuel delivery rate were adjusted as necessary to achieve maximum brake torque at the specified speed and load. The data were then recorded for the emulsified fuel.

At the beginning of the test sequence, procedure was altered slightly. Immediately following operation of the engine with diesel fuel alone, the emulsified fuel was introduced without changing the fuel delivery setting (rack). A data sheet was completed at this condition and the fuel delivery was adjusted to regain the load specified for the run condition. Another data sheet was completed, and then the injection timing was optimized for the emulsified fuel, and another data record was made. This procedure proved to be cumbersome and time-consuming in terms of the information that was obtained, and it was abandoned in favor of the run sequence described above.

The general process, therefore, consisted of a test run with diesel fuel at a particular speed and load, followed immediately by a test run using emulsified fuel at the same speed and load, with injection timing optimized

TABLE 2.1 - ENGINE TEST CONDITIONS

Engine rpm	Nominal IMEP, psi	Nominal Vol. % Water-In-Fuel
Daedalean Emulsions		
1000	60	10, 20
	75	10, 20
	90	10, 20
2000	68	10, 15, 20
	82	10, 15, 20
	96	10, 15, 20
2500	70	20
	85	20
	100	20
Dynatrol Emulsions		
1000	60	6.4, 14.5, 23.5
	75	5.2, 12.0, 20.2
	90	4.3, 10.0, 17.0
2000	68	3.3, 7.8, 13.5
	82	2.6, 6.3, 11.2
	96	2.1, 5.0, 8.9

in both cases. This process of alternating between diesel fuel and emulsified fuel was followed throughout the program. Immediately following the second run of each pair (the run involving emulsified fuel), the fuel delivery to the engine was stopped, the electric motor was engaged, and a measurement of engine friction was obtained at values of the oil and coolant temperatures within 5 F of those observed during the test run. The friction data were utilized for the calculation of indicated engine performance during the data reduction process.

The fuel rates were measured by recording the time required for the consumption of a particular weight or volume of fuel. Both weight and volume determinations were obtained during test runs with diesel fuel alone; the values were subsequently compared during the data reduction process. During test runs using emulsified fuel, volume measurements only were obtained. During the tests involving the DAI emulsifier, flow rates of emulsion were measured by the volume technique. With the Dynatrol emulsifier, however, the flow of water and the flow of fuel were measured independently.

Values of variables such as temperatures, pressures, engine speed, and engine load were monitored continuously throughout the data acquisition period in order to assure that deviations from specified test conditions did not occur. Determinations of fuel time and exhaust smoke level were repeated several times during each test run in order to assure that representative values were obtained.

Following the acquisition of data at a particular speed and load, the load was reset to the next value in the sequence of desired torques, and the test data were recorded. After the three runs at one speed were completed, the speed was changed to the next value, and the three load points were examined. The entire sequence of test conditions was repeated four to six times for each fuel-water emulsion concentration that was examined. This degree of repetition allowed a statistical analysis to be conducted on the replicated data.

Measurements of gaseous exhaust emissions were obtained during one set of test runs for each fuel-water emulsion concentration. The measurements were performed during the time required for acquisition of the other test data.

2.3 Data Reduction and Calculation Procedures

During the performance of the testing program, the engine data were recorded on preprinted forms that included a photograph of the oscilloscope traces. Subsequent data reduction processes converted the raw data into customary quantities and applied the necessary correction factors. This section is intended as a summary of the data processing steps that were performed.

The data acquisition form provided to the engine operator specified the test conditions at each point by designating the desired speed, load, injection timing, and fuel (diesel fuel or emulsion water content). In addition, values for the coolant outlet temperature and the oil sump temperature were specified. A sample of the data sheet is included as Figure 2.6.

The desired test conditions were set and maintained by the engine operator, and the observed values of all parameters were recorded after a stable operating condition had been achieved. For the tests with the DAI emulsifier, water content of the fuel was obtained on a daily basis by averaging the water content of centrifuged samples obtained at hourly intervals throughout the testing process. The Dynatrol emulsifier did not require the production of fuel in excess of the engine requirements, and water content was measured directly by calibrated flowmeters.

The engine air flow was obtained from the calibration curve of the laminar flow element. The flow rate indicated by the observed pressure drop across the metering element was corrected for the filter pressure drop, the ambient (barometric) pressure, and the ambient temperature in order to obtain the value in standard cubic feet per minute. This result was then converted to pounds per hour.

The observed engine speed and dynamometer beam load were used, along with the dynamometer constant, to obtain brake horsepower (BHP). Similar data, obtained while the engine was being motored, were used to calculate friction horsepower (FHP). The brake horsepower was corrected for ambient conditions using the correction factor described in SAE J816b for diesel engines, and the corrected brake and friction horsepower values were added to yield the indicated horsepower (IHP).

The values for engine displacement, speed, and horsepower were utilized for the calculation of the brake, friction, and indicated mean effective pressures. The mean effective pressure is proportional to torque and is useful as a plotting parameter for the comparison of other quantities.

The flow rates of diesel fuel were obtained in terms of the time required for consumption of a known mass of fuel; the measured values were converted to units of pounds per hour. The flow rates for both diesel fuel and fuel-water emulsion were also measured by means of a volumetric technique; the time required for consumption of a measured volume of fuel was recorded. In this case the density of the fuel, at the temperature of the metered flow, was obtained from the API gravity (Appendix A) and used in the conversion from volume to mass. When emulsions were measured with the volumetric meter, a density was calculated from the actual measured water content (obtained by centrifuging samples of emulsion and measuring the volume of water in the bottom of the centrifuge tubes), the fuel density, and the water density. Both densities were obtained at the temperature of the fluid in the metering system. For emulsions, flow rates were calculated for both the total liquid flow and the diesel fuel flow into the engine; the latter quantity was used in subsequent calculations of specific fuel consumption.

Date ____________________ Run No. __________________

Conditions: ____

____

____

Firing Load __________ lb. Speed ________________ RPM

Air Flow: Inlet Δ P ______________ in H_2O LFE Δ P ____________ in H_2O

Fuel Volume __________________ ml ____________________ counts _________ Rev.
Fuel Volume __________________ ml ____________________ counts _________ Rev.
Rack Micrometer _____________ in. Crankcase Pressure ____________

Exhaust Pressure _____________ Oil Pressure __________________ psi

Water Pressure in ______ out ________

Temps:
1. Water in ________ °F
2. Water out ________ °F
3. Oil in N.A. °F
4. Oil Sump ________ °F
5. Oil out N.A. °F
6. Fuel(pump) ________ °F
7. Inlet air (LFE) ________ °F
8. Inlet air (eng) ________ °F
9. Exhaust ________ °F
10. Room ________ °F
11. Fuel(meter) ________ °F

Exhaust Pressure ______________ in. Hg Barometer _____________ in. Hg

Humidity: DB______ °F WB ________ °F ___________ % RH

Motoring Data: Load __________ lb Oil Temp. ________ °F

Water in ______ °F Water Out ________ °F

Smoke ________ Bosch HC __________ CO __________ NO_x ____________

Calculated:

Air Flow ________ lb/hr

BHP ___ FHP ___ IHP ___

bmep ___ fmep ___ imep ____

Fuel flow __________ lb/hr

BSFC ____ ISFC ____ Photo

Vol. Eff. ________ %

Ther. Eff. _______ %

F/A Ratio _______

FIGURE 2.6 - CLR ENGINE TEST DATA SHEET--EMULSIFIED FUEL

The ratio of the fuel flow and the engine horsepower output yields the specific fuel consumption; this value was calculated for both the brake and indicated power. Another useful ratio, the engine thermal efficiency, was obtained from the indicated horsepower output, the fuel rate, and the lower heating value of the fuel. In addition, the ratio of the fuel mass flow rate and the air mass flow rate yields the fuel-air ratio, a typical indicator of engine loading.

Since the data acquisition process at each engine test point and each fuel blend was repeated from four to six times, it was possible to calculate the mean and standard deviation for each set of similar runs. The Student's t-distribution was then utilized to obtain the interval that would contain the mean with a 90% confidence. With this information available for each set of data, it was possible to specify whether or not a difference existed between the mean of the runs with diesel fuel and the mean of the runs with fuel-water emulsion at each test condition.

In general, no calculations were performed on the gaseous emissions data. The numerical values (in parts per million or percent) obtained from the sampling instruments were used for comparing the effects of emulsified and baseline fuels. An exception to this procedure was the calculation of a carbon balance between the carbon in the fuel and the carbon in the exhaust, as determined by the concentration data for unburned hydrocarbons, CO, and, most importantly, CO_2.

blank

3. DISCUSSION OF TEST RESULTS

In this section, we discuss the effect of emulsified fuels on the most pertinent engine data obtained in this test series. Some tables and graphs of data are presented in the text for easy reference, while supplementary tables and graphs are included in Appendix B. This section also contains qualitive discussions of the effect of these emulsified fuels on general engine operation. The data obtained with the two emulsification devices are compared only to try to show consistency in results when emulsified fuel is used. It is not intended that there should be a competition between the emulsifiers; indeed, such an approach would be inappropriate since little can be said about the type or qulaity of water-in-fuel emulsions produced by the two devices.

3.1 Indicated Specific Fuel Consumption

Statistically significant (90% confidence level or greater) improvements in indicated specific fuel consumption (ISFC) were obtained through use of emulsified fuel for twenty of thirty-six engine test conditions (10 of 18 for each emulsification device). The average improvement at these 20 test points was 3.0%. At 1000 and 2000 rpm, the common test speeds for both emulsifiers, the average reduction in ISFC was 1.9% and 3.1%, respectively. At 2500 rpm (Daedalean emulsifier only) the average established reduction was 5.1%. Average fuel consumption values (along with other engine performance and emissions data) for each test condition are shown in Appendix Tables B-1 and B-2 for Daedalean and Dynatrol emulsions, respectively these ISFC values are graphed as functions of indicated mean effective pressure (IMEP) in Figures B-1 through B-6 (Daedalean) and Figures B-7 through B-12 (Dynatrol) of this same appendix.

Figures 3.1 through 3.3 show the percentage change in ISFC as a function of emulsified fuel-water content for each engine speed/load test condition used in conjunction with the Daedalean emulsifier. At 1000 rpm (Figure 3.1) one statistically established reduction (2.7%) was obtained at the highest IMEP (90 psi) with the highest water content used (20%). Better results were obtained at 2000 rpm (Figure 3.2), where seven of nine test points showed ISFC improvements ranging from 2.4 to 4.8% (average of 3.7%). These reductions occurred at all three engine loads for 15 and 20% water content. The optimum water content appears to be 15%, since the largest reductions in ISFC occur at this point. At 2500 rpm (Figure 3.3), where only 20% water content was tested, a 5.1% reduction was obtained at the two higher load points. The lightest engine load (70 psi IMEP) barely missed showing a reduction (2.5%) at the 90% confidence level. The reduction actually passes at about 85% confidence, however.

Summarizing the results obtained with the Daedalean emulsions: of the 10 test conditions at which a statistically established reduction in ISFC was found, the average improvement was 3.9%. Considering only the reductions that occurred at the two lower engine speeds, the average improvement was 3.6%.

The corresponding data obtained with emulsions produced by the Dynatrol device are shown in Figures 3.4 (1000 rpm) and 3.5 (2000 rpm).

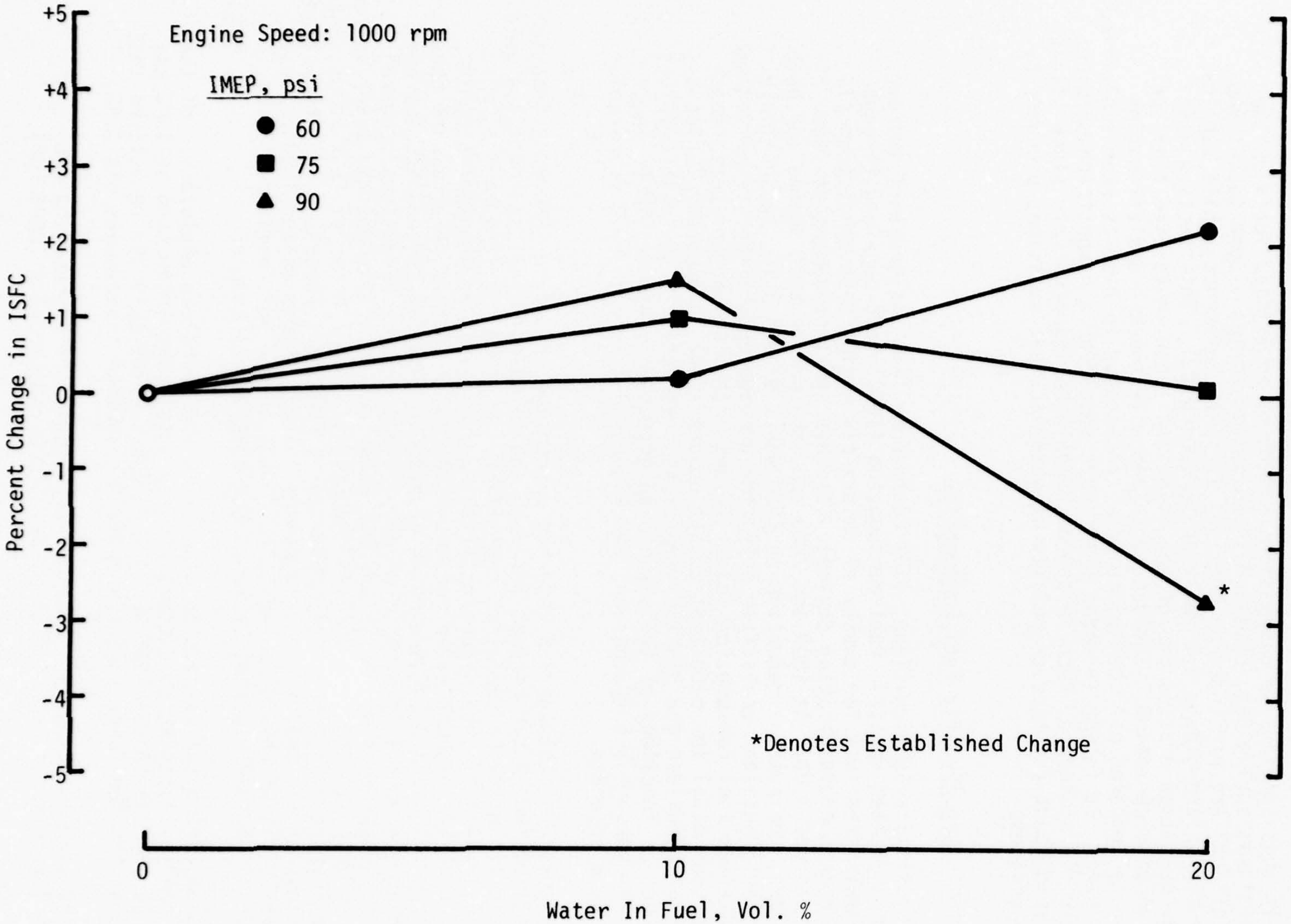


FIGURE 3.1 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

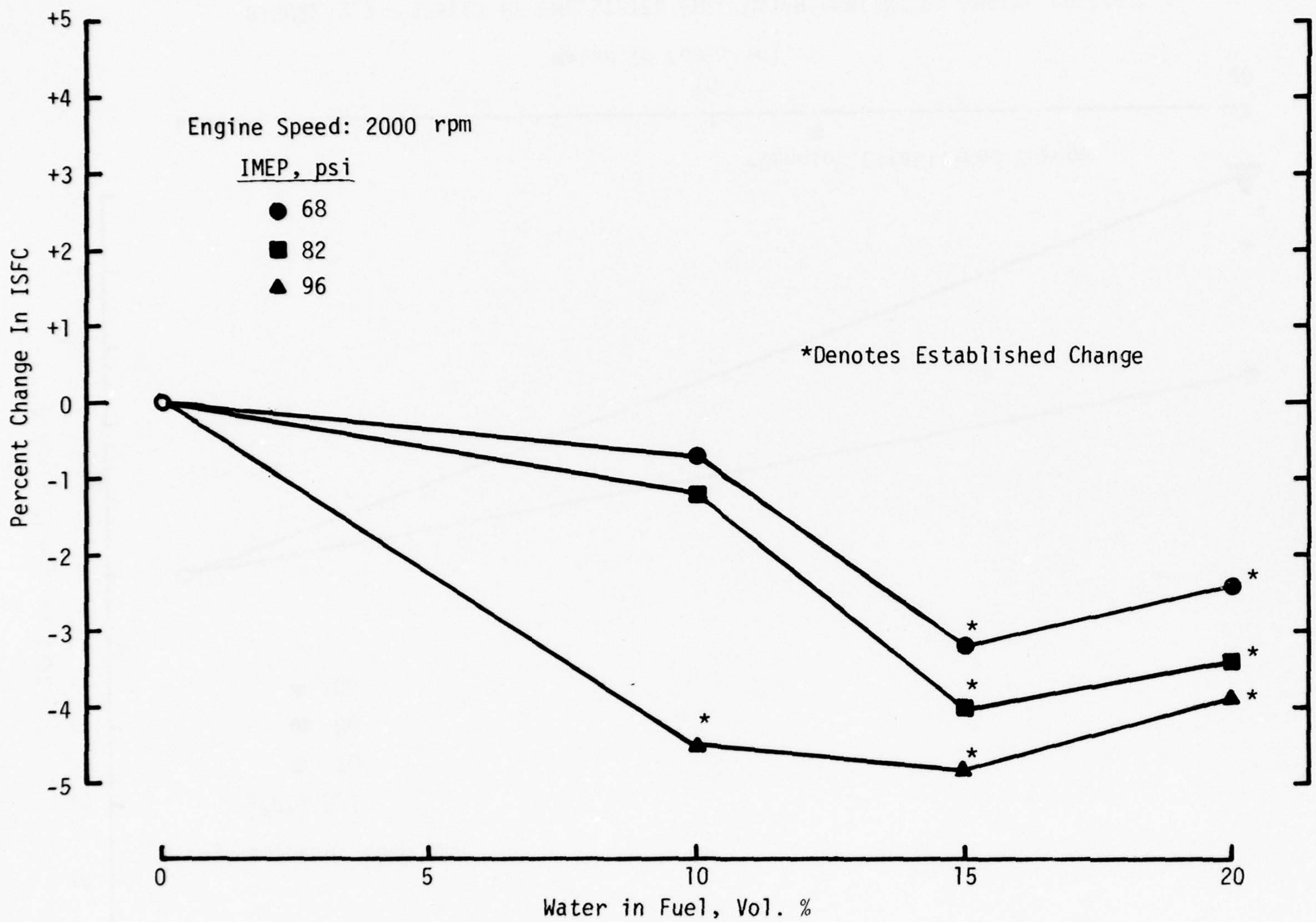


FIGURE 3.2- EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

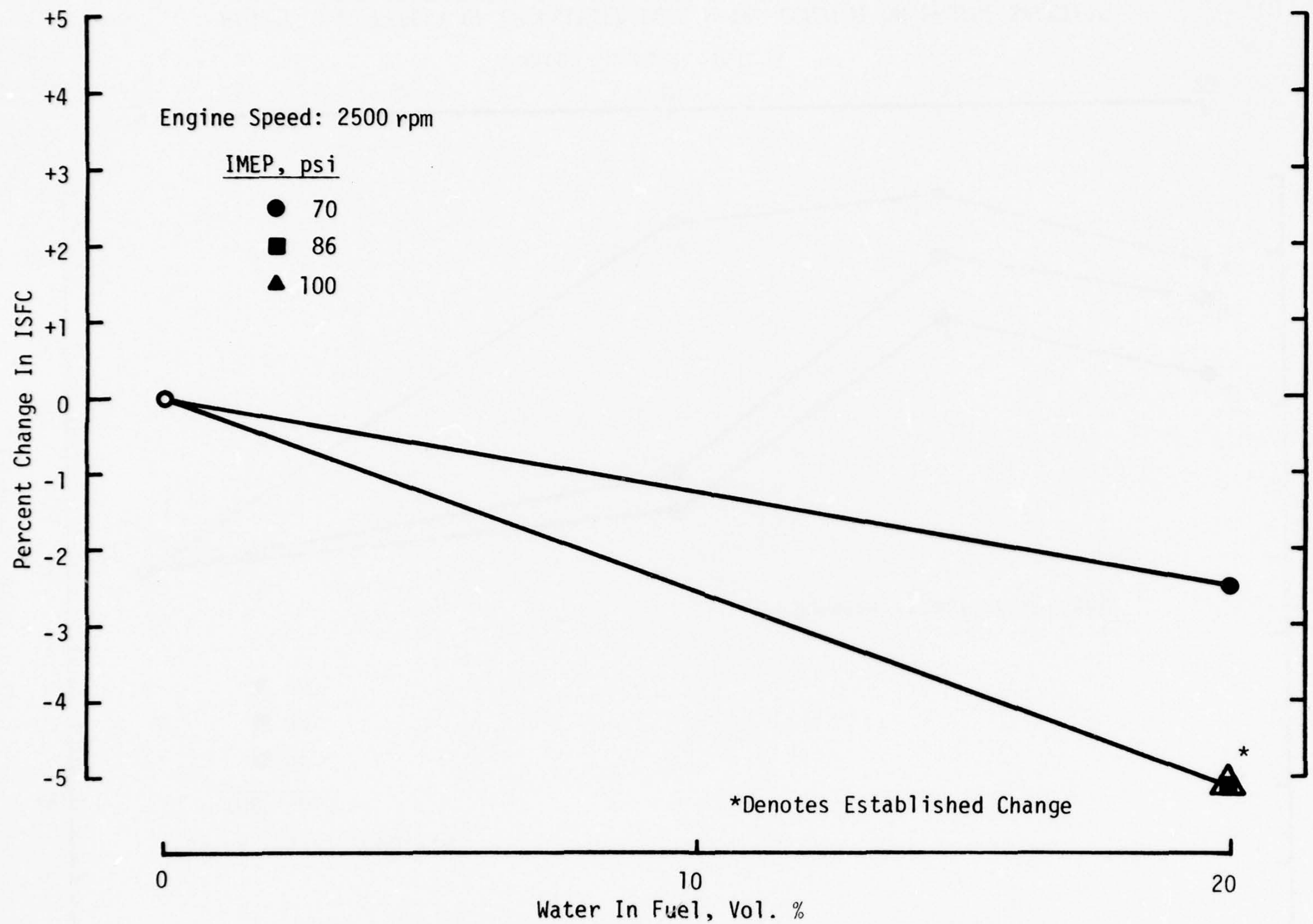


FIGURE 3.3 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

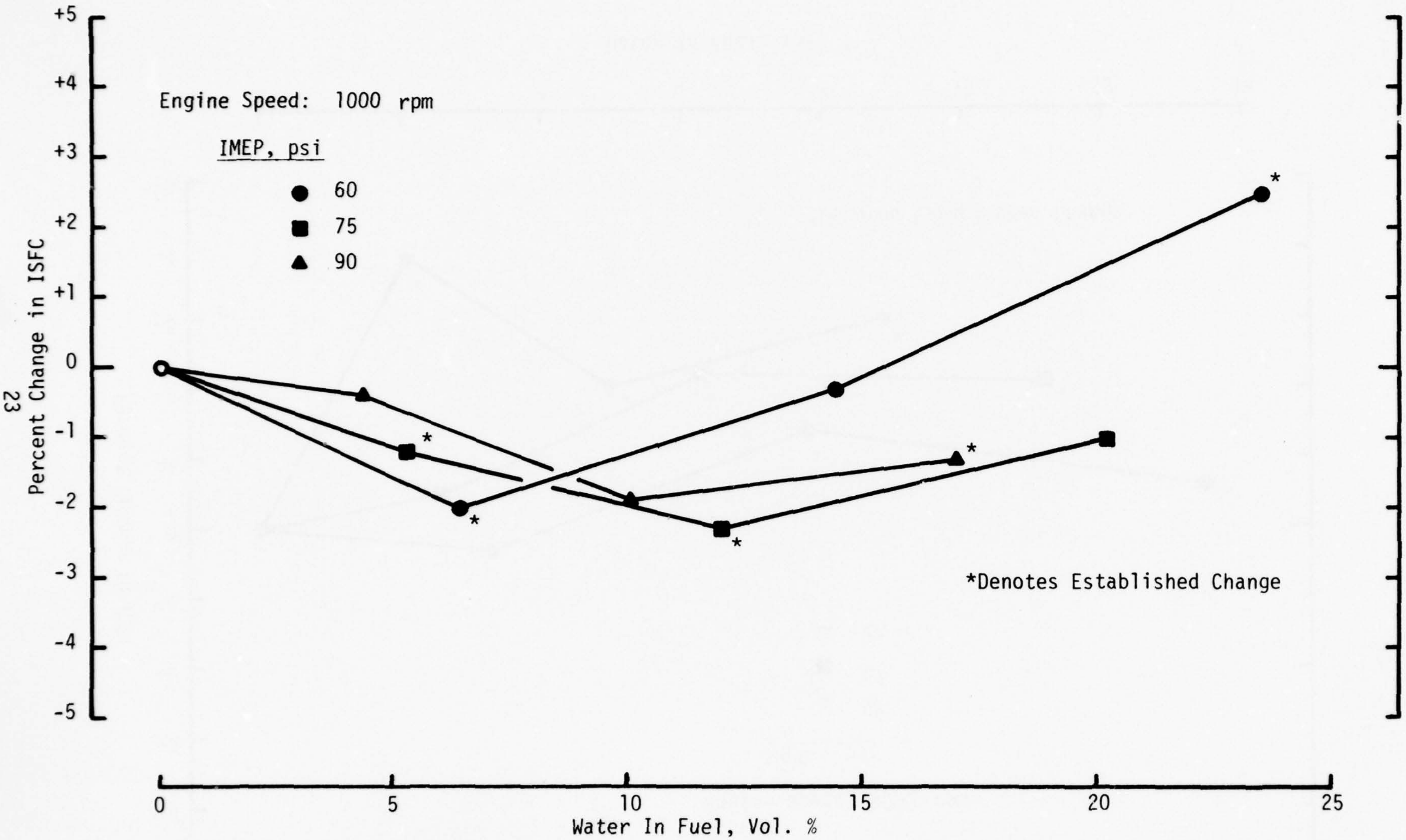


FIGURE 3.4 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

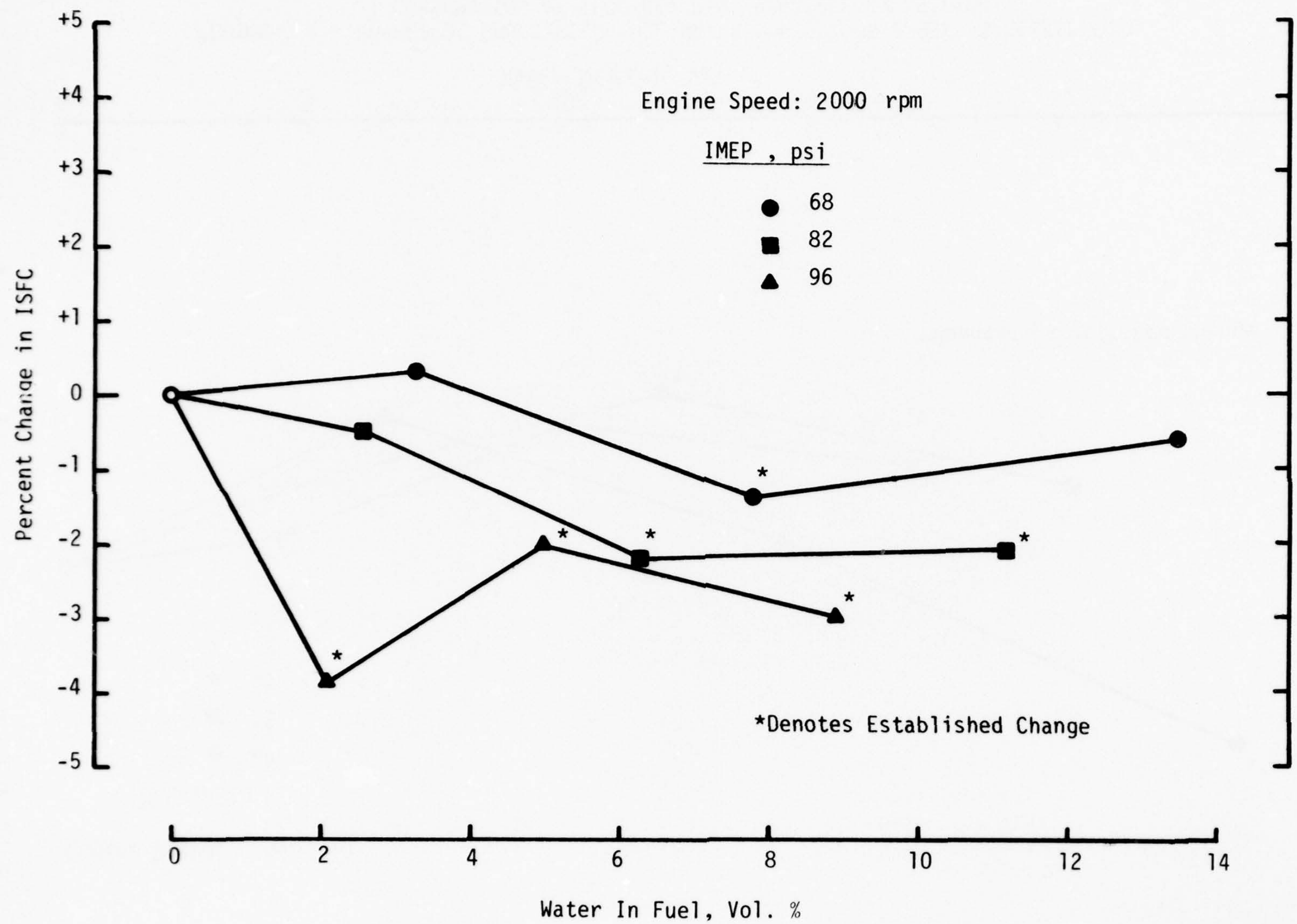


FIGURE 3.5 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DYNATROL EMULSIFIER

For tests at the lower speed, the fuel-water content varied from about 4 to 23.5% by volume, a greater range than was employed in tests with the Daedalean emulsions. It appears that the lighter loads benefited from low (5 to 6%) water content, while the maximum load point required somewhat more water input in order to effect a reduction in ISFC. The lowest IMEP condition suffered a degradation in fuel consumption at the maximum water content. In all, five of the nine test points had statistically established changes in ISFC: four decreases ranging from 1.2 to 2.3% (average of 1.7%) and one increase of 2.5% at the light load-high water content condition. These data definitely show that water content can and should be optimized to the engine operating condition.

At 2000 rpm (Figure 3.5), fuel-water content ranged from about 2 to 13.5%. Established reductions in ISFC were found at six of nine test conditions; these reductions ranged from 1.4 to 3.9%, with an average of 2.4%. Improvement occurred for all three water contents at maximum IMEP, for two points at the medium IMEP, and for only one point at the lowest IMEP. Note that some of the reductions occurred with quite low water content. These data complement those obtained at this engine speed with Daedalean emulsions (Figure 3.2) in that the ISFC for the higher load is again shown to be more susceptible to improvement than is fuel consumption at lower IMEP. Or, alternately, it appears that optimization of the fuel-water content to obtain a reduction in fuel consumption is less critical at higher load than at lighter loads.

To summarize, it was found that use of emulsified fuel from the Dynatrol device resulted in improved ISFC at 10 test points, with an average reduction of 2.1%. There was one instance of an increase in fuel consumption that was probably due to use of too great a water content at the particular engine condition.

3.2 Exhaust Smoke Density

Although Bosch smoke numbers were obtained for all test points, it is our opinion that only Bosch numbers at least equal to 1.0 should be analyzed, since this smoke level corresponds to a PHS smoke meter opacity of less than 2%, which is below the limit of visibility. Not only is smoke density below this level not significant, but such data tends to have a large amount of variation or scatter. Repeatability is much better at Bosch numbers of 1.0 or above. However, all smoke data is presented in summary Tables B-1 and B-2 of the appendix.

The smoke data obtained with Daedalean emulsions are shown in Figure 3.6. It can be seen that consistent reductions in smoke density were obtained. At 1000 and 2000 rpm, where more than one water content was used, the decrease was approximately linear with water content. In general, baseline smoke numbers were reduced by one-third to two-thirds, depending on fuel-water content. The average reduction for the seven test points shown in the figure was approximately one-half(45%).

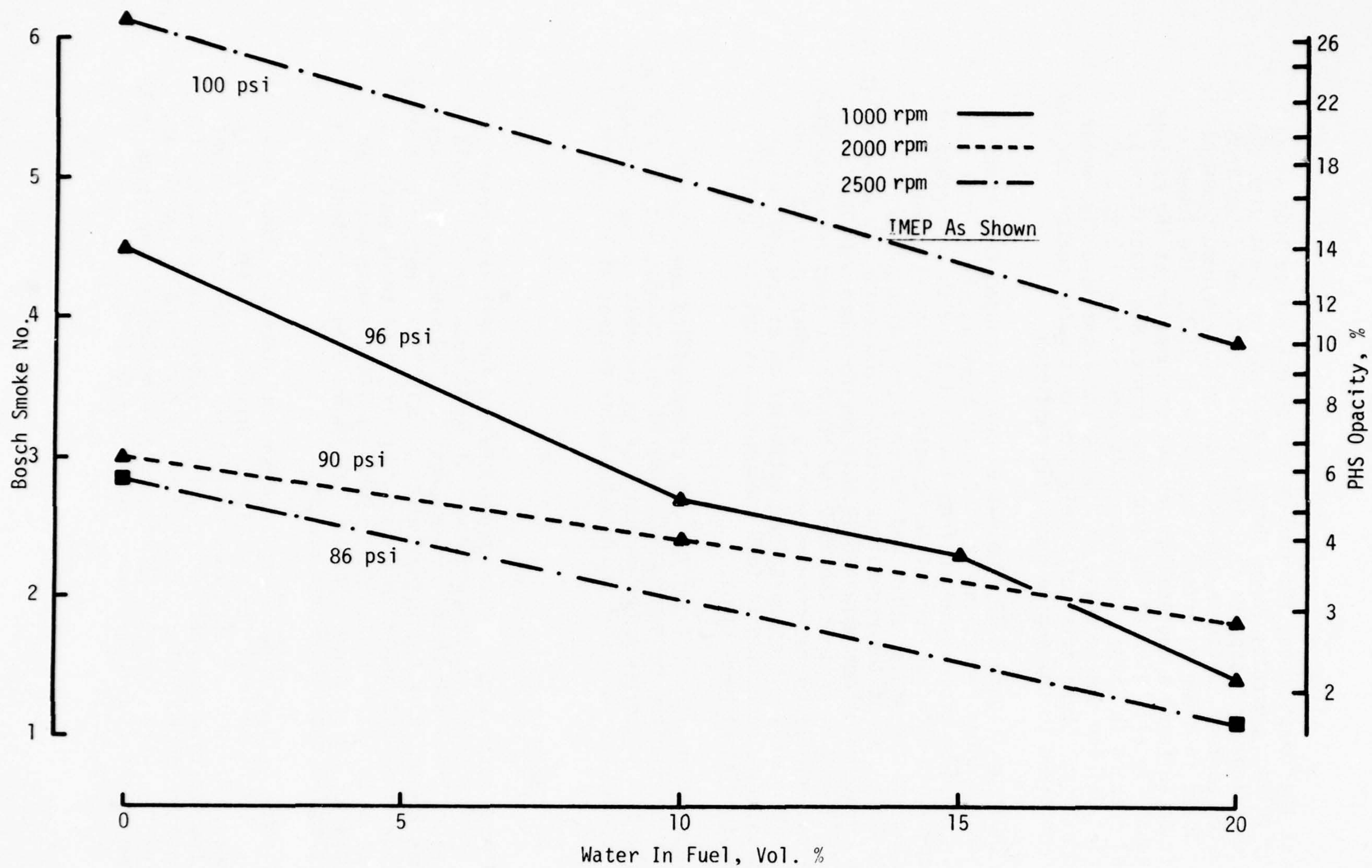


FIGURE 3.6 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST SMOKE DENSITY AT 1000, 2000, AND 2500 REV/MIN--DAEDALEAN EMULSIFIER

Smoke data obtained with the Dynatrol emulsions are shown in Figure 3.7. The smoke reduction trend is not as consistent here as for the previous data. It appears that the maximum fuel-air ratio condition (96 psi IMEP) at 2000 rpm might have benefited from more water in the fuel, while smoke density at the other conditions is not sustantially influenced by the emulsified fuel. However, in no case was an increase in smoke found to occur. The reductions range from approximately 10 to 36%, and the average reduction was approximately 17%.

Therefore, significant (visible) smoke density with emulsified fuel from both devices was reduced at every condition but one (where no change was observed).

3.3 Oxides of Nitrogen

Oxides of nitrogen (NO_x) concentrations obtained in tests with the Daedalean emulsifier are presented in Appendix Table B-1, while the percentage change in concentration as a function of fuel water content is shown in Figures 3.8 through 3.10. It can be seen that NO_x was reduced by the use of emulsified fuel at all speed-load points except one. In general, the highest IMEP condition required more water content than did the other two load points at each speed in order to achieve a similar percentage reduction in NO_x. In other words, a given water content resulted in a smaller reduction at maximum load than it did at lower IMEP values. This is a reasonable result since peak flame temperature and fuel-air ratio during combustion (two primary factors in NO_x formation) are highest at maximum load. In any case, the reductions in NO_x were significant and ranged from 9 to 41% (average 29%) at 1000 rpm, from 14 to 58% (average 40%) at 2000 rpm, and from 28 to 44% (average 38%) at 2500 rpm. The lone increase in NO_x was less than 10%. The average reduction for all operating conditions was approximately 35%.

The corresponding data for the Dynatrol emulsions are contained in Table B-2 and shown in Figures 3.11 and 3.12. NO_x concentration was lowered at 14 of 18 test conditions. Two increases (3 and 26%) occurred at the highest IMEP at 2000 rpm, where water content was low (2 to 9% by volume). This behavior is consistent with that observed during the Daedalean tests; i.e., it appears that maximum load conditions require more water to produce a significant reduction in NO_x. In fact, the one condition in the Daedalean test series at which increased NO_x was noted was at maximum load at 2000 rpm with 10% water content, the lowest value used.

Reductions obtained with the Dynatrol device at 1000 engine rpm ranged from 10 to 59%, (average of 30%); at 2000 rpm, the range was 14 to 39%, (average of 26%). The average reduction at these test points was 28%. The decrease in NO_x was a function of increasing fuel-water content at 1000 rpm, but at 2000 rpm this trend was not as well defined.

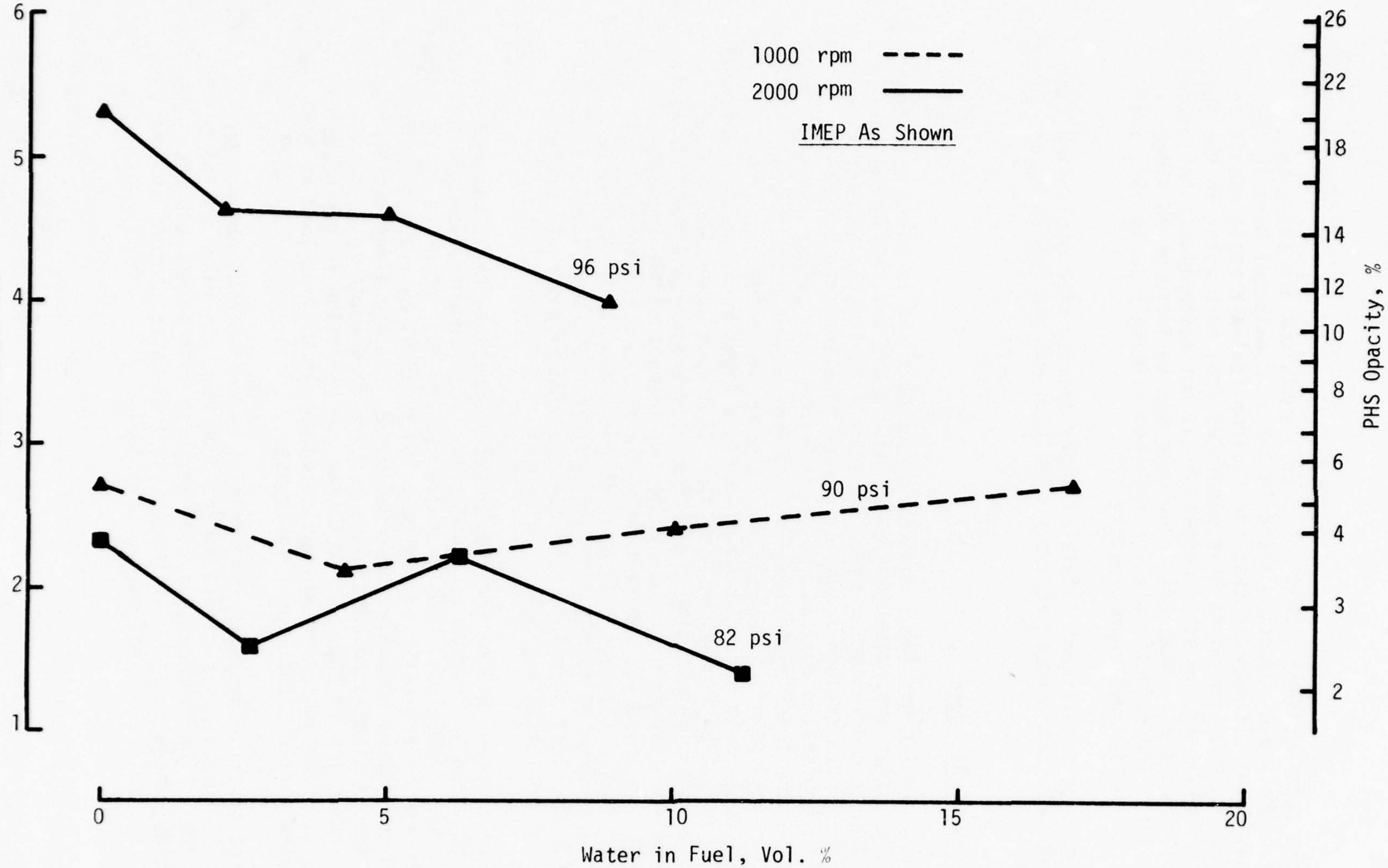


FIGURE 3.7 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST SMOKE DENSITY AT 1000 AND 2000 REV/MIN--DYNATROL EMULSIFIER

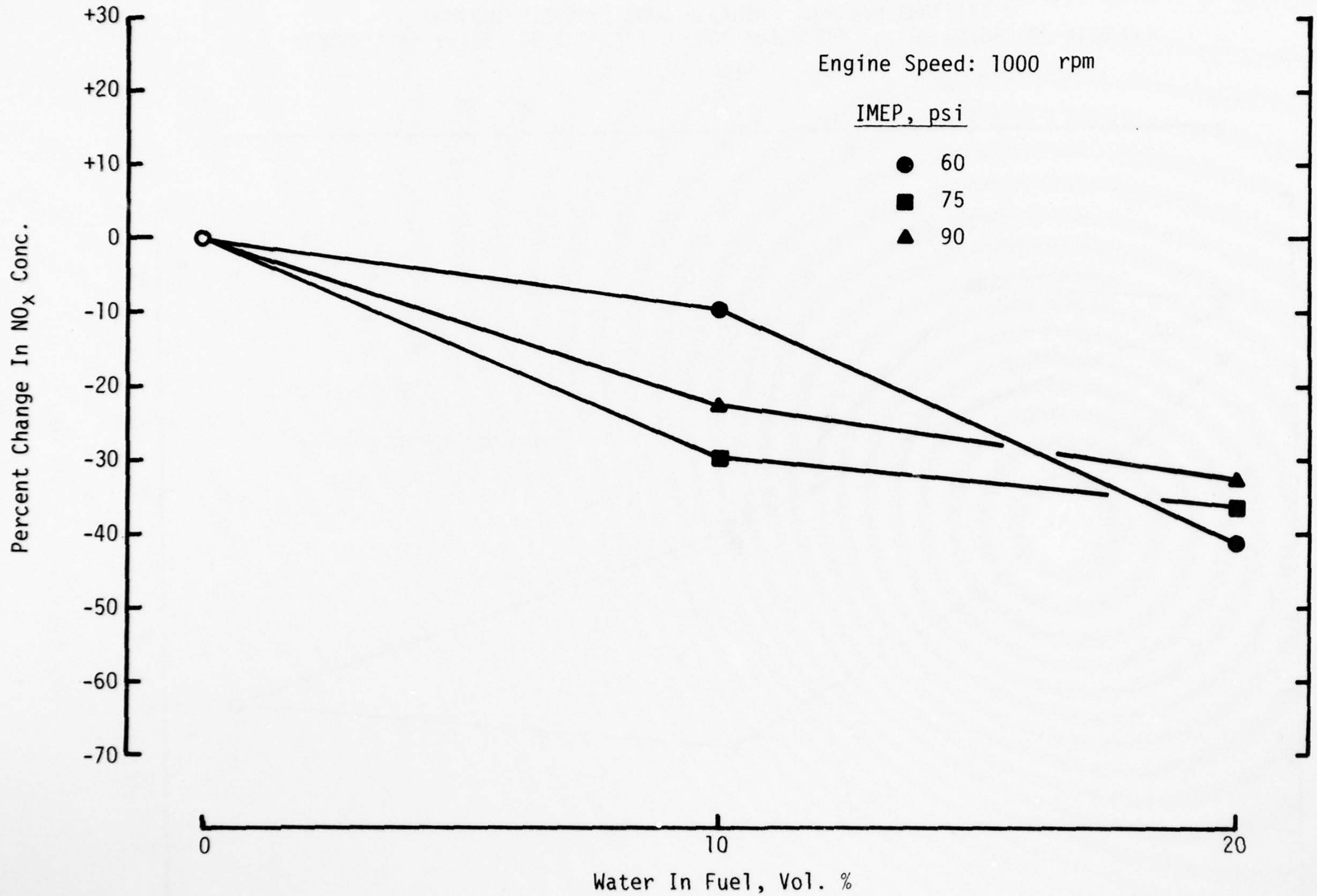


FIGURE 3.8 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF NITROGEN CONCENTRATION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

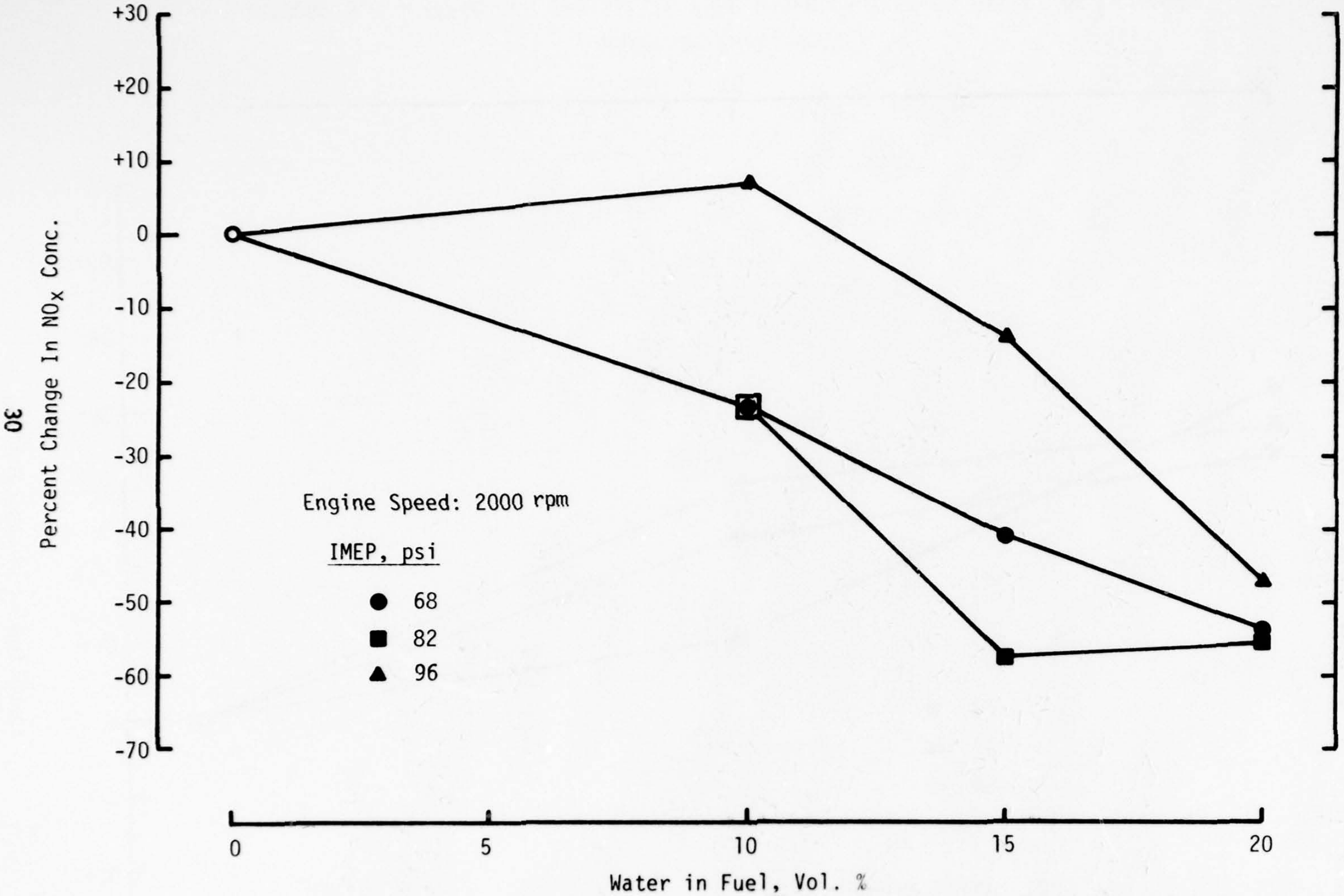


FIGURE 3.9- EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF NITROGEN CONCENTRATION AT 2000 REV/MIN--DADALEAN EMULSIFIER

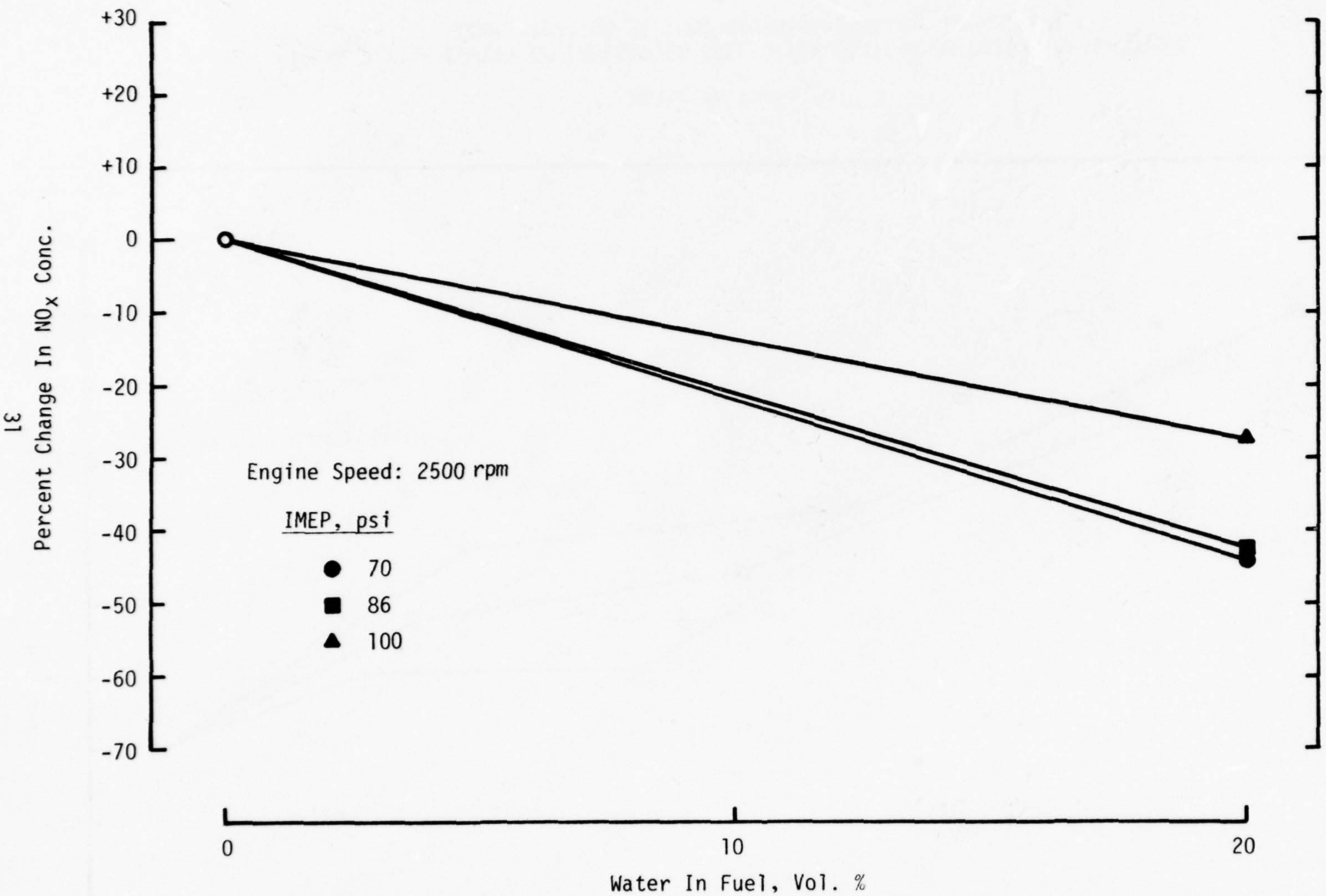


FIGURE 3.10 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON OXIDES OF NITROGEN CONCENTRATION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

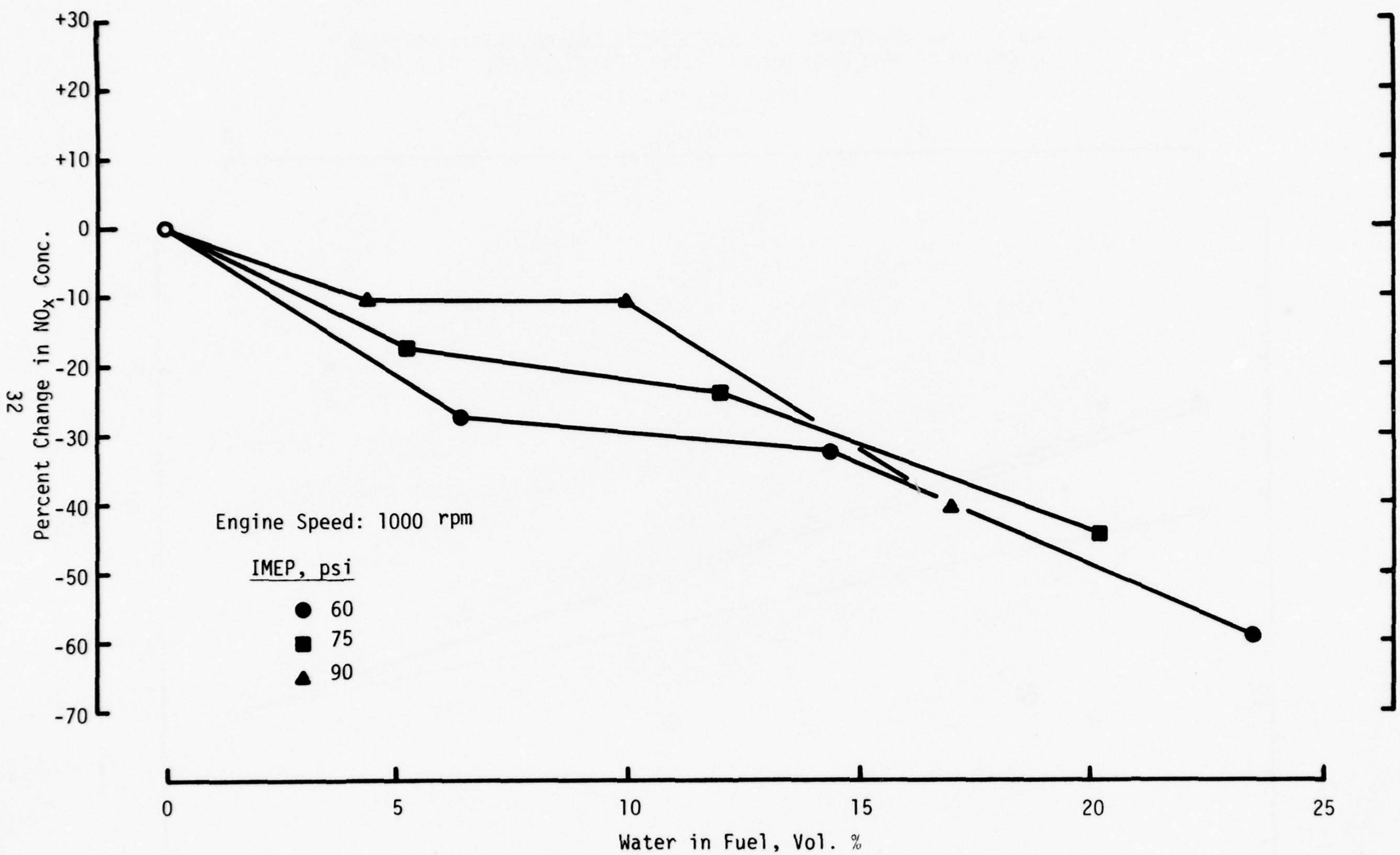


FIGURE 3.11 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF NITROGEN CONCENTRATION AT 1000 REV/MIN--DYNATROL EMULSIFIER

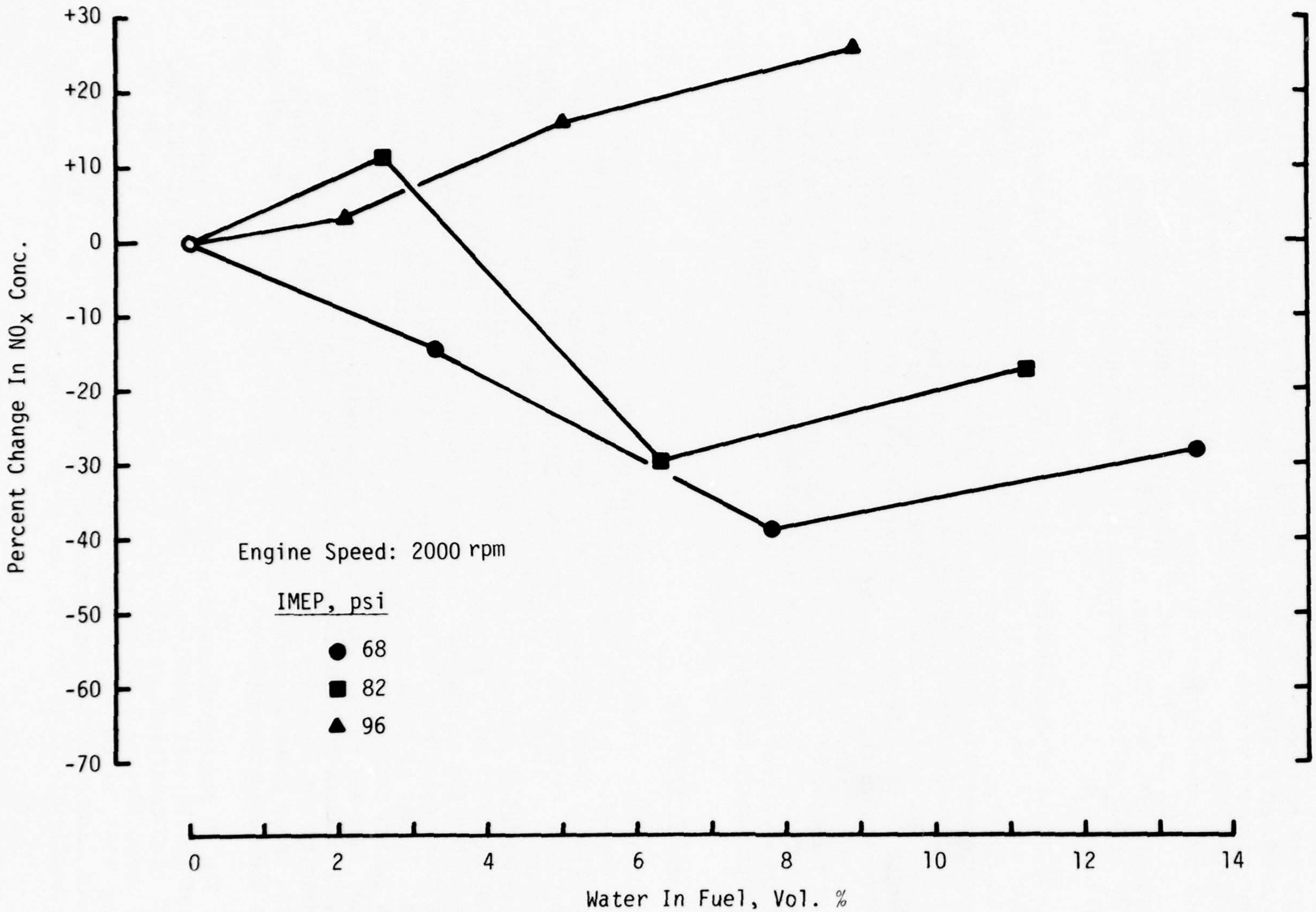


FIGURE 3.12 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON OXIDES OF NITROGEN CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

3.4 Unburned Hydrocarbons

Concentrations of unburned hydrocarbons (UBHC) were increased at all but one test condition when the engine was operating on emulsified fuels produced by the Daedalean device. The percentage change of these concentrations are shown in Figures 3.13 through 3.15. It can be seen that at 1000 and 2000 rpm, where more than one water content was tested, that hydrocarbon concentration generally increased with the water content of the fuel. At 1000 rpm, the range of concentration increase was from 17 to 59% (average of 39%), at 2000 rpm, 6 to 41% (average of 19%), and at 2500 rpm, from 25 to 65% (with an average of 45%). The average increase for all tests was 34%.

With use of the Dynatrol emulsions, UBHC concentration increased at 12 of the 18 test points, including all nine at 1000 rpm and three of nine at 2000 rpm. These changes are shown in Figures 3.16 and 3.17. At the lower speed, the increases ranged from 5 to 43% (average of 21%), while at the higher speed the spread was from a negligible 2% to 131% (average of 78%). The decreases in concentration at 2000 rpm were from 1 to 17%, with an average of 6%. The overall average increase at this speed was 49%. It should be stated that changes of only a few percent would probably not be statistically significant if multiple tests had been performed, as were done in the case of the fuel consumption data. In any case, the trends in hydrocarbon concentration were somewhat ambiguous, and it did not appear that even a general functional relationship existed between UBHC concentration and water content.

3.5 Carbon Monoxide

With conventional (baseline) diesel fuel, it is almost always true that an increase in carbon monoxide (CO) concentration is accompanied by an increase in smoke density, and vice versa. However, when emulsified fuel produced by both devices was used, CO concentration increased at about two-thirds of all the test conditions; many of these conditions were those where significant decreases in smoke density were observed. It is known that formation of CO is extremely sensitive to highly localized fuel-air ratios within the combustion chamber, which are often completely unrelated to the gross calculated fuel-air ratio for a given cylinder or the entire engine. It may be that, for this particular engine, the formation of carbon (which ultimately agglomerates into smoke particles) is less sensitive to local fuel-air ratio. The factors which relate combustion of emulsified fuel with changes in localized fuel-air ratios might include changes in fuel density and viscosity, which in turn would affect fuel spray droplet size and spray penetration, two important factors in the mixing of fuel and air in the combustion chamber.

The CO concentrations obtained with Daedalean emulsions increased at 12 of the 18 test conditions, including all six conditions at 1000 rpm, four of nine conditions at 2000 rpm, and two of three at 2500 rpm. At the lowest speed (Figure 3.18) the range of these increases was 26 to 106% (average 59%), at the medium speed (Figure 3.19) the changes ranged from 35 to 70% (average 53%), and at the highest speed condition (Figure 3.20) from a negligible 3% to 50% (average of 26). The overall average increase

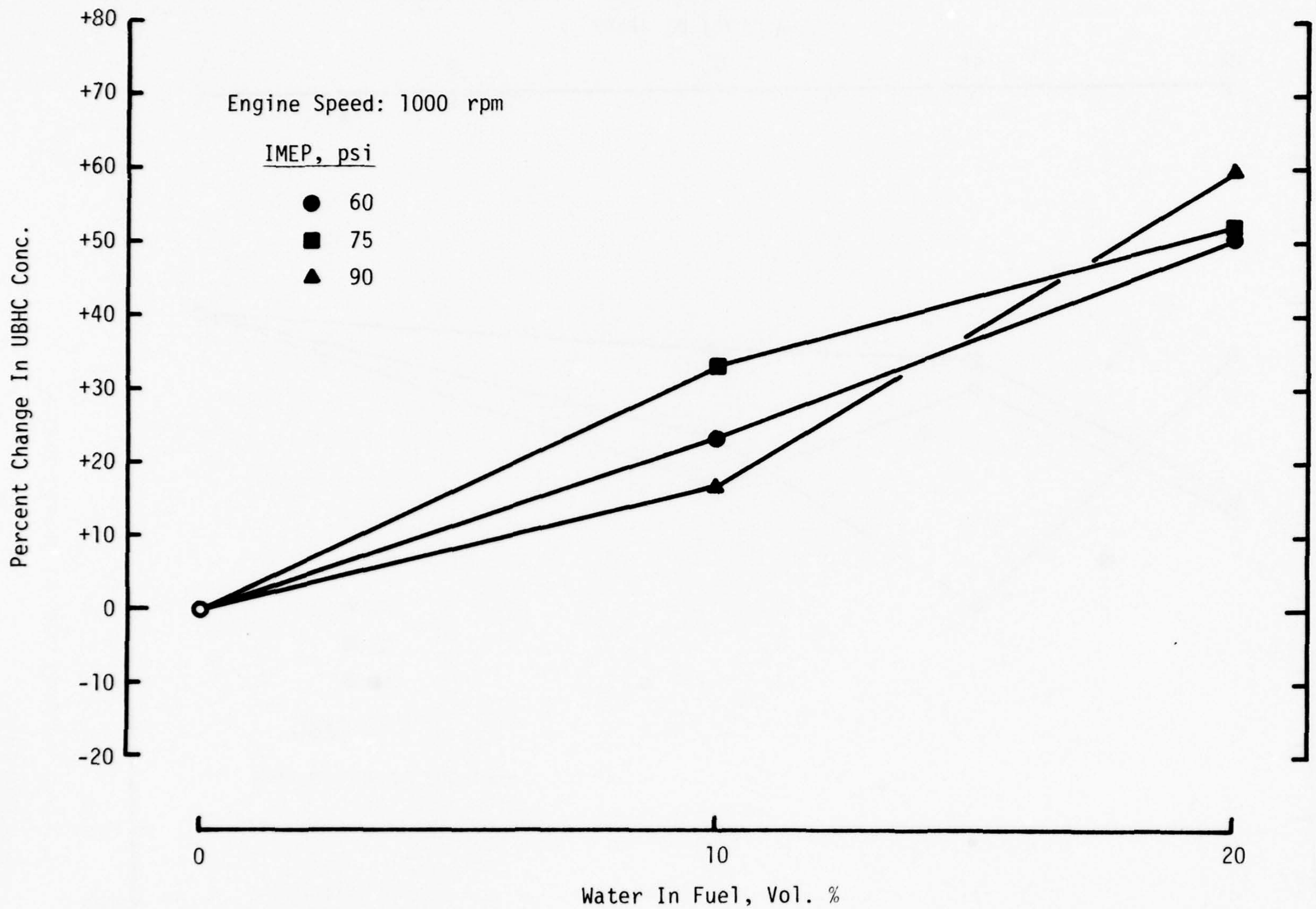


FIGURE 3.13 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED HYDROCARBONS CONCENTRATION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

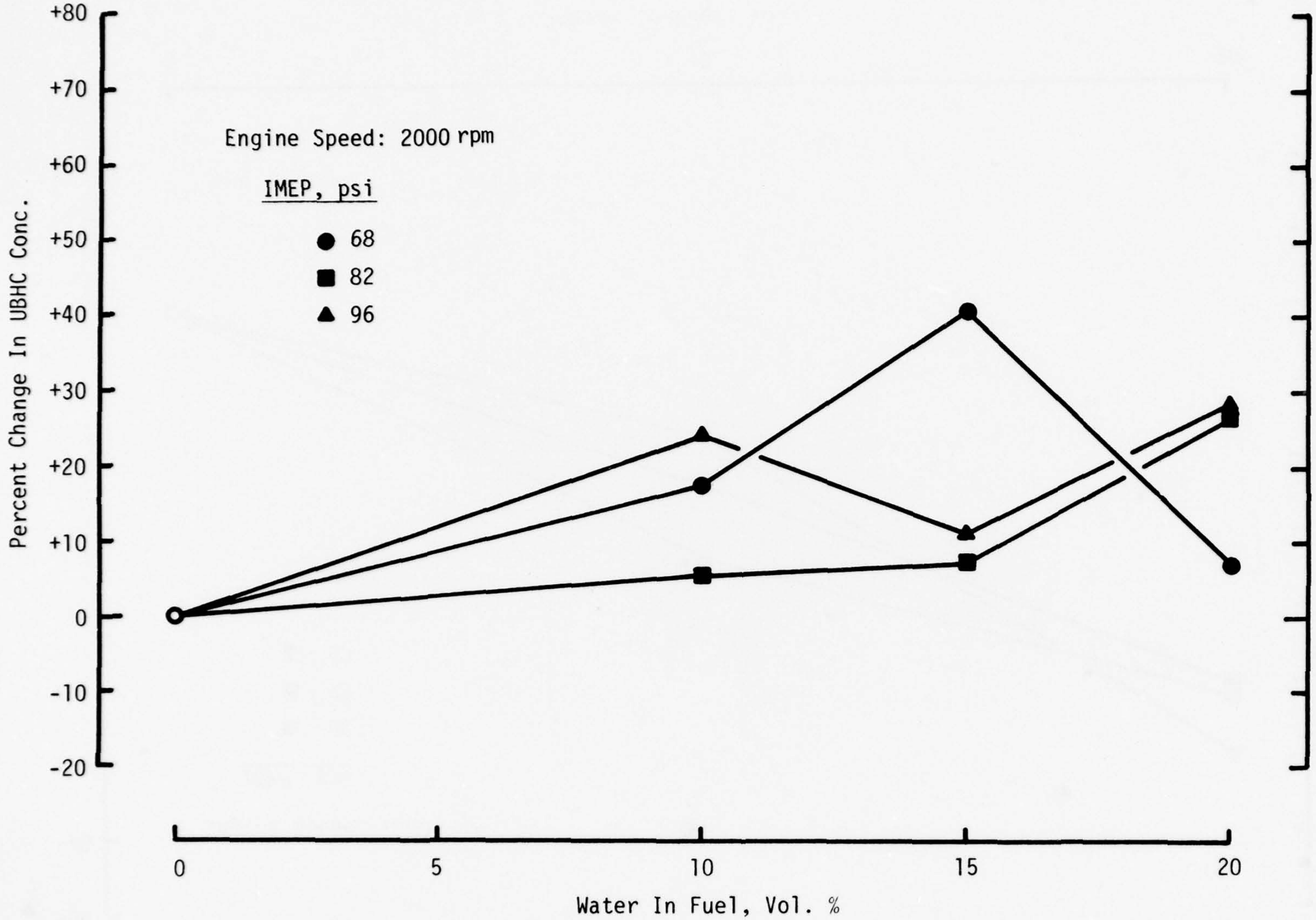


FIGURE 3.14 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED HYDROCARBONS CONCENTRATION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

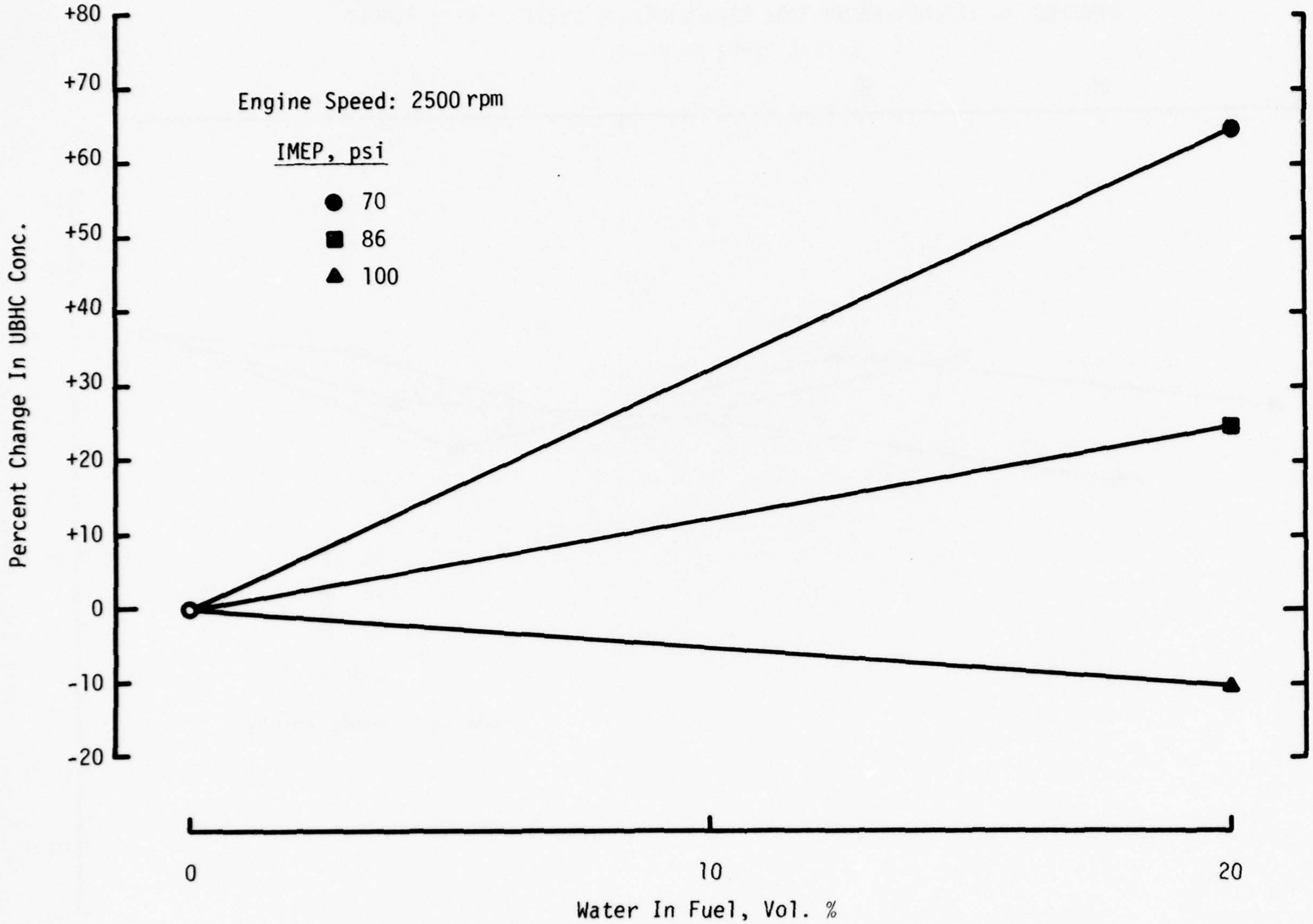


FIGURE 3.15 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON UNBURNED HYDROCARBONS CONCENTRATION AT 2500 REV/MIN--DAEDALEAN EMUSLIFIER

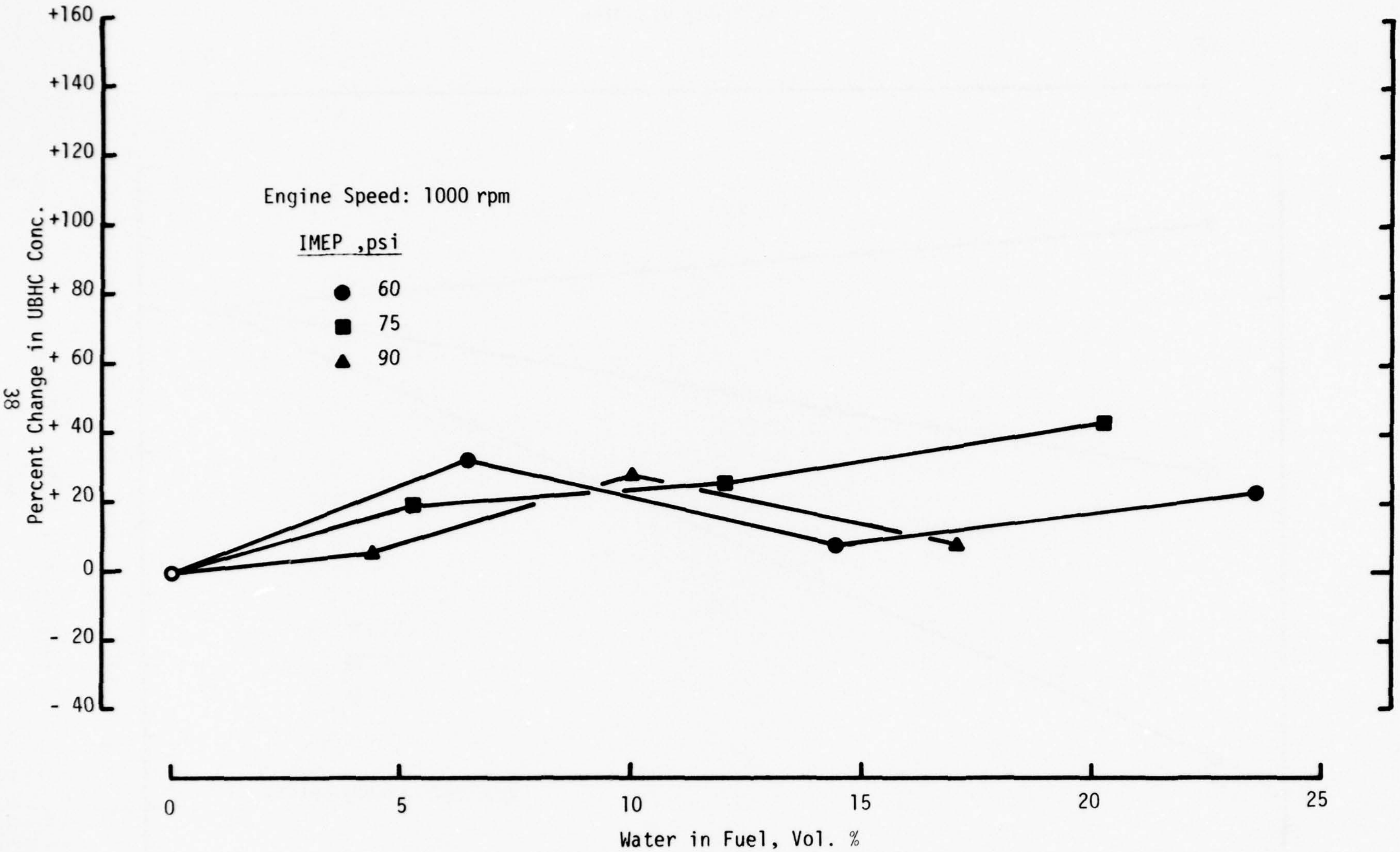


FIGURE 3.16 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED HYDROCARBONS CONCENTRATION AT 1000 REV/MIN--DYNATROL EMULSIFIER

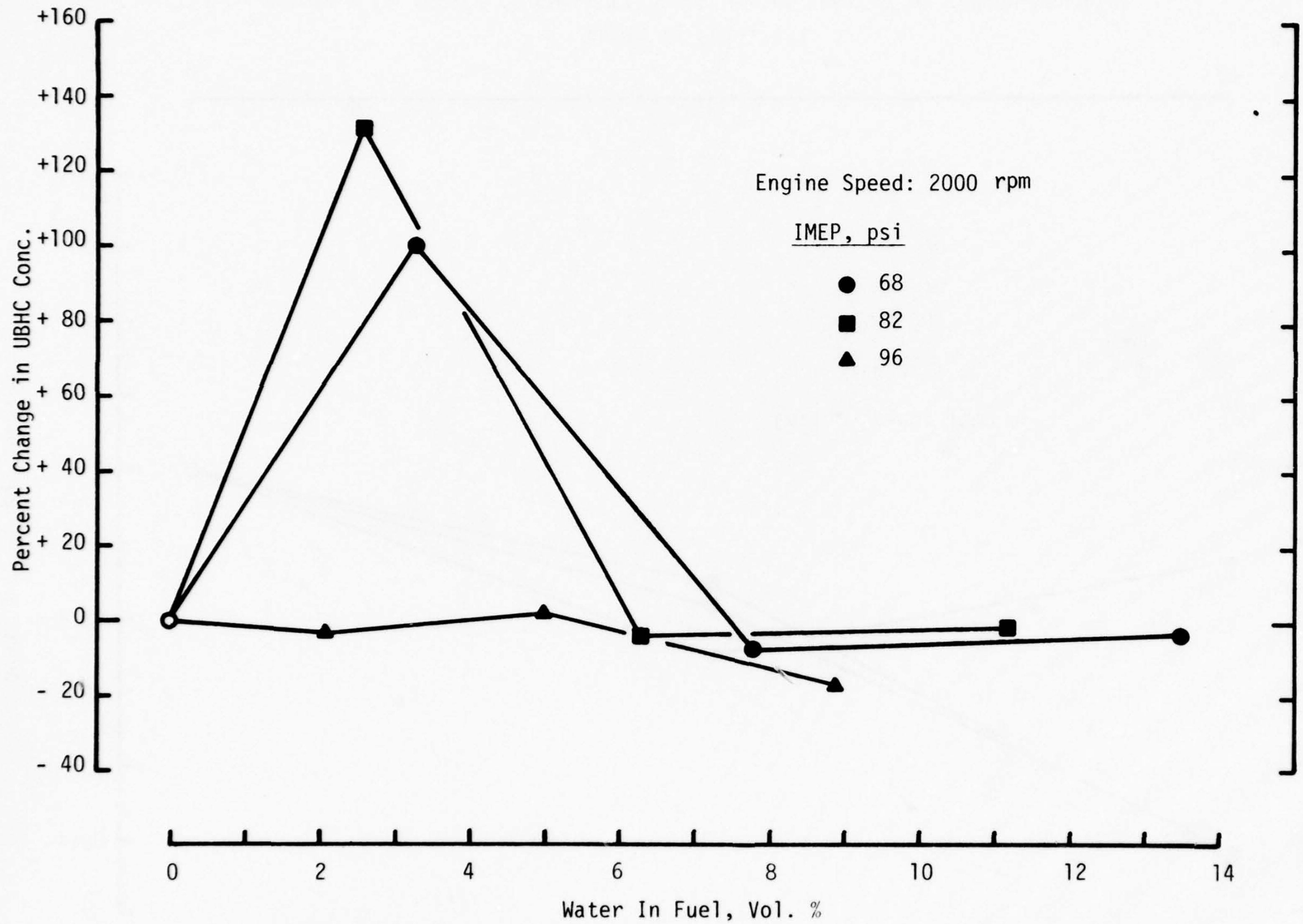


FIGURE 3.17 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON UNBURNED HYDROCARBONS CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

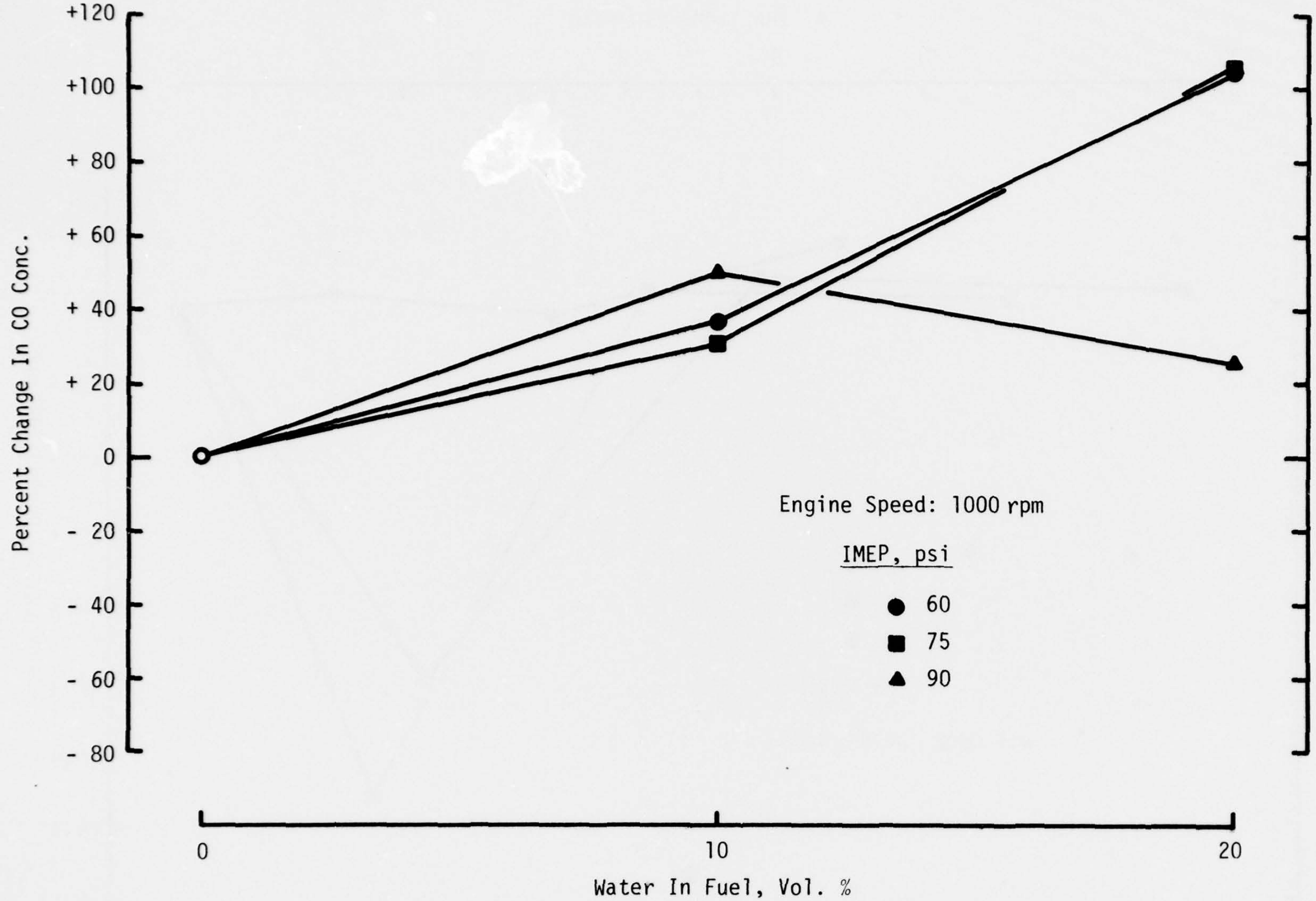


FIGURE 3.18 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE CONCENTRATION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

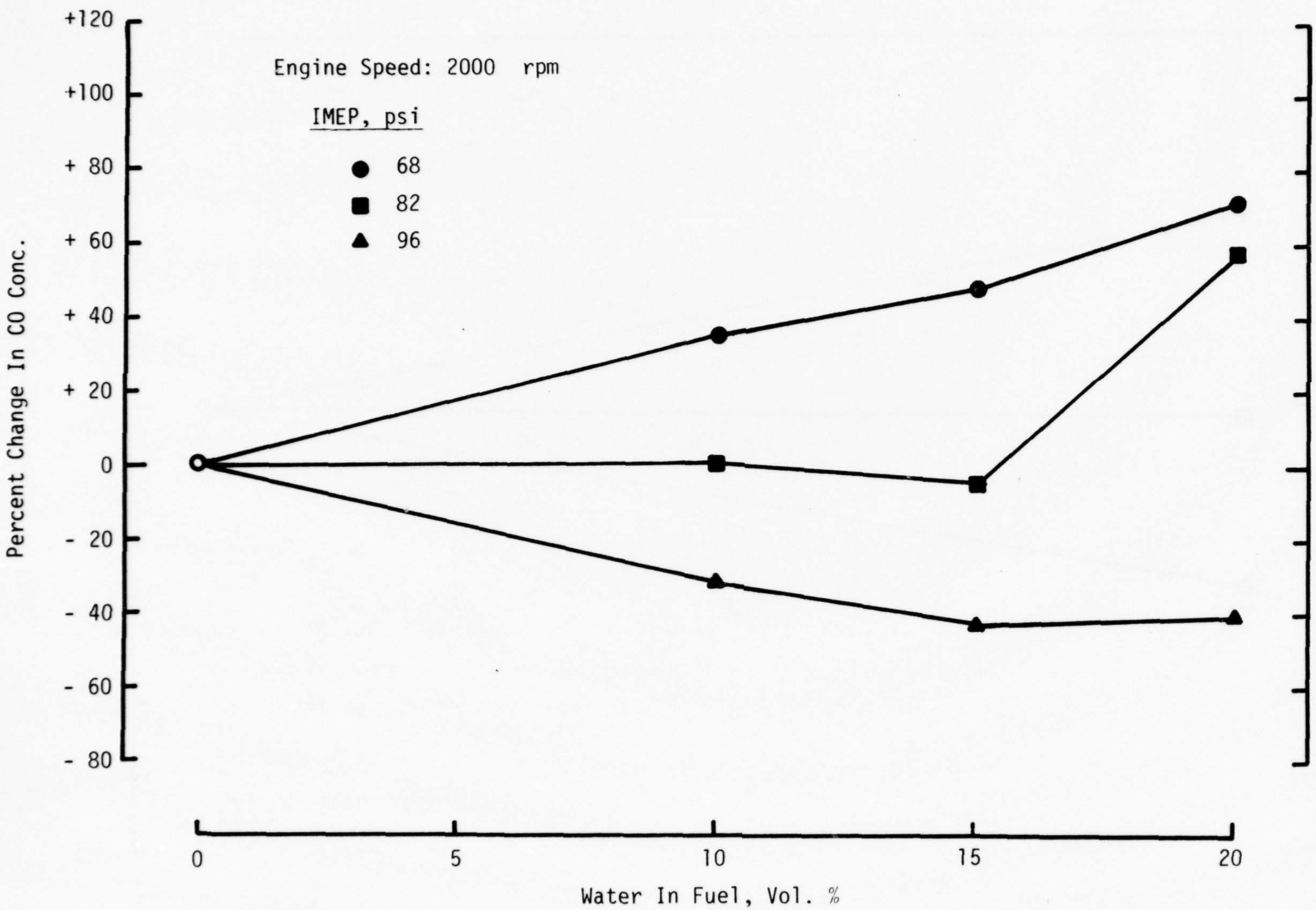


FIGURE 3.19 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE CONCENTRATION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

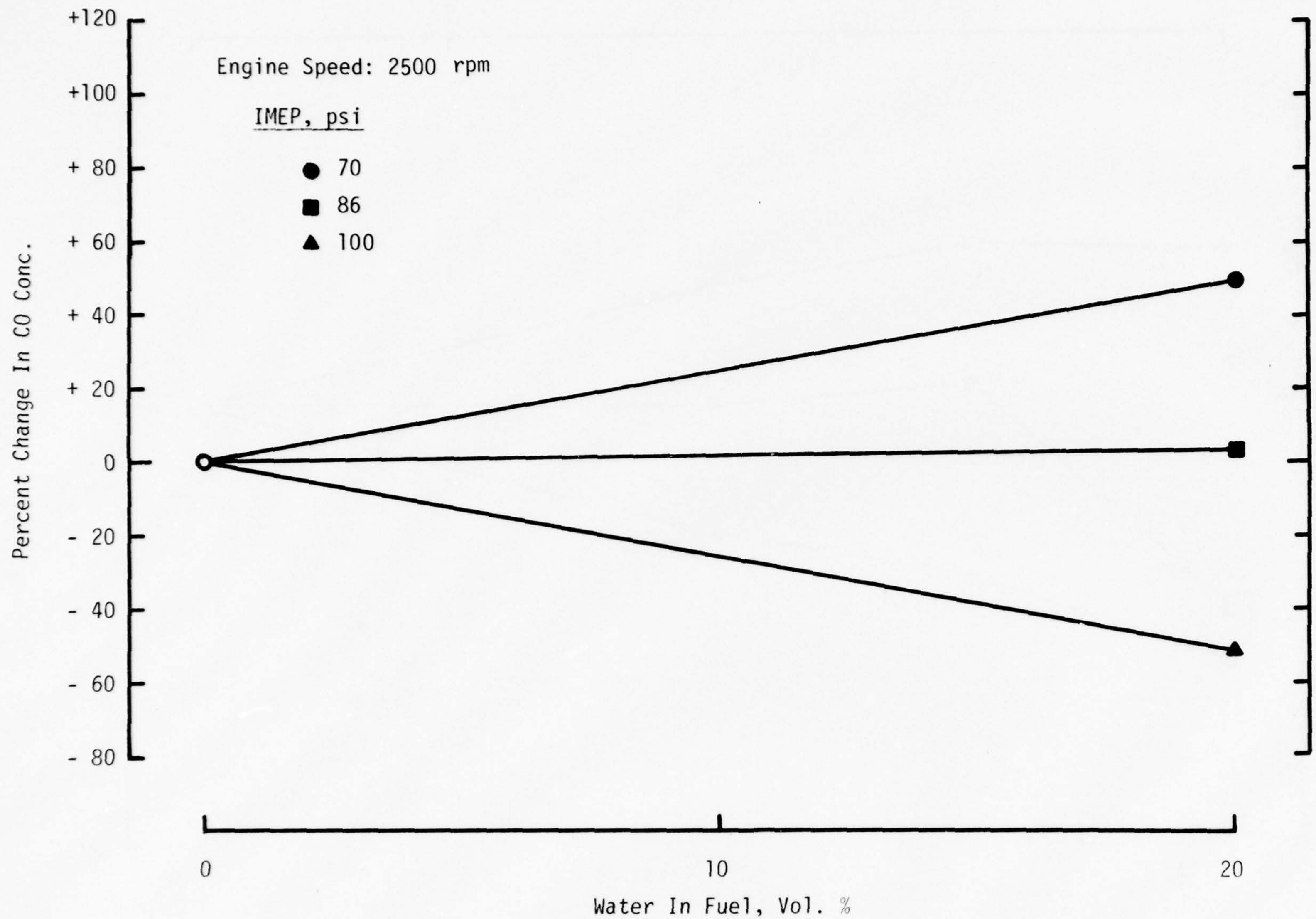


FIGURE 3.20 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON CARBON MONOXIDE CONCENTRATION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

at all three engine speeds was 51%, and for the two lower speeds only, 56%. There were five instances (mostly at the higher speed/load conditions) where CO concentration decreased; these changes ranged from 6 to 52%, with an average of 35%.

Similar changes in CO were found with the Dynatrol emulsions. Increases in concentration occurred at eleven test points, while decreases were found at six conditions (concentration at one condition was unchanged). At 1000 rpm (Figure 3.21), increased concentration went from 8 to 172% (average of 56%), and 2000 rpm (Figure 3.22) the range was from 11 to 90% (average of 46%). The overall average increased at both speeds was 53%. Decreased concentration was again observed principally at higher loads at 2000 rpm. These decreases were from 21 to 37%, with an average of 32%.

3.6 Carbon Dioxide Measurement and Carbon Balance Calculations

Carbon Dioxide (CO_2) was measured in order that a carbon balance calculation could be made. The usual purpose of this calculation is to determine the intake air mass flow rate for an engine (usually a large engine) for which conventional air flow measurement is impractical. This situation obviously did not pertain to the engine used in this test program since air flow rate was readily measured by a laminar flow element. A better reason to measure CO_2 concentration in the exhaust is to use the data as an indicator of combustion efficiency (higher CO_2 concentration indicates more complete combustion). However, it is also necessary to determine the amount of water vapor in the exhaust in order to complete the desired analysis, but no such measurement was performed in these tests. In any case, the measurement of CO_2 concentration and the subsequent carbon balance calculation were performed at the sponsor's request.

This calculation also involves concentrations of UBHC and CO, but, of course, CO_2 is the predominant carbon-carrying exhaust constituent and thus plays almost the total role in the exhaust gas part of the carbon balance. (For these tests, CO_2 concentration was in the range of 4 to 10%, or 40,000 to 100,000 parts per million; by comparison, maximum concentrations of UBHC and CO were approximately 3,000 and 6,000 ppm, respectively.) Accurate fuel consumption rate measurement and knowledge of the fuel carbon content are required for the other part of the carbon balance. Agreement between exhaust and fuel carbon is usually within 1 or 2% if the pertinent quantities have been accurately measured. Any discrepancy is usually due to an error in the CO_2 concentration measurement, since the fuel consumption rate and fuel carbon content are generally not subject to significant error. This is certainly true of these tests, where the fuel consumption measurement was known to be very accurate and repeatable, and fuel carbon content was precisely known from the complete fuel analysis shown in Appendix A.

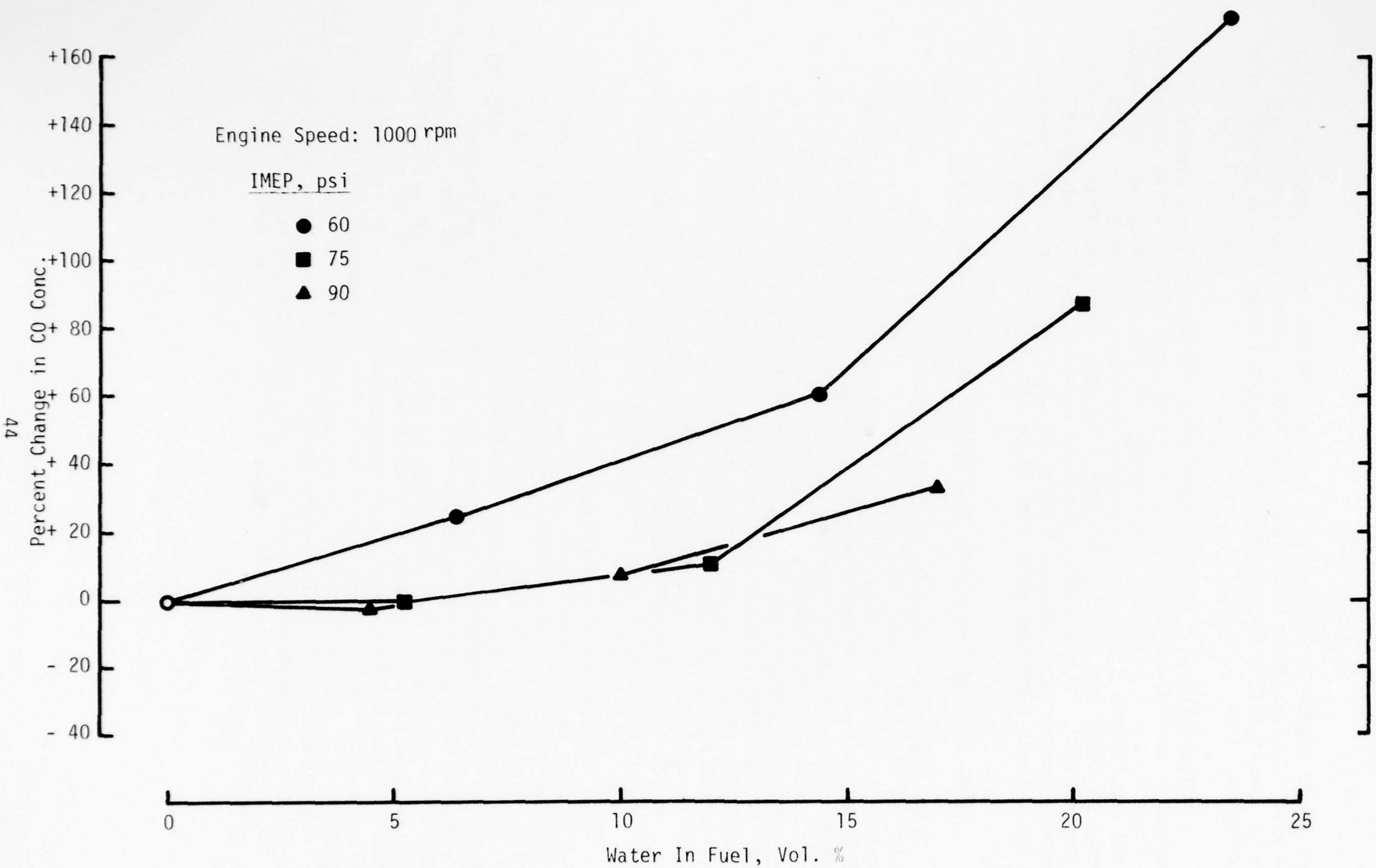


FIGURE 3.21-EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE CONCENTRATION AT 1000 REV/MIN--DYNATROL EMULSIFIER

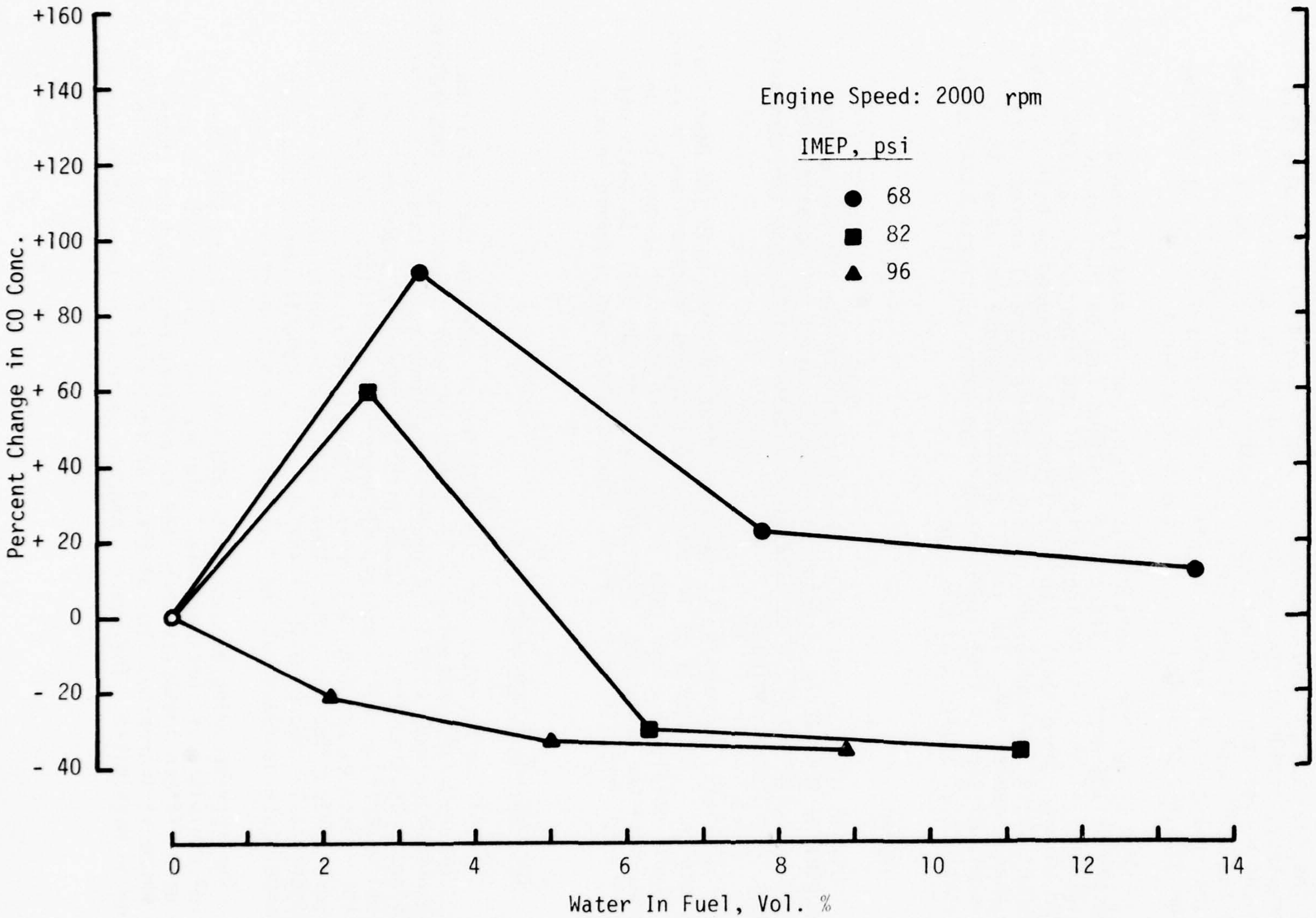


FIGURE 3.22 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON CARBON MONOXIDE CONCENTRATION AT 2000 REV/MIN--DYNATROL EMULSIFIER

However, the carbon balance calculation performed here showed a substantial discrepancy, with the exhaust carbon being 10 to 20% lower than the fuel carbon contribution. Attempts were made to resolve this discrepancy, including the search for a leak in the emission sampling line and conversion of CO and CO_2 concentrations to a wet basis to agree with the UBHC data. It was finally concluded that calibration of the CO_2 instrument was in error. Recalibration was not feasible at the time so the data are presented here as they were obtained.

Even though they contain this error, the CO_2 data can be used to determine the general effect of emulsified fuel on this exhaust constituent, if this is considered to be of any importance. Briefly stated, it was found that, with emulsified fuel produced by both devices, instances where CO_2 decreased outnumbered those where it increased by more than three to one. The overall average decrease was about 3%, a very small difference that might not hold up under replicate measurements and statistical analysis of the data.

3.7 Oxygen

Oxygen (O_2) concentrations were measured solely for the purpose of completing the matrix of principal diesel exhaust gas constituents, since interpretation of these data yield little insight into the combustion process in a diesel engine.

To briefly summarize, it was found that in tests with the Daedalean emulsions that the number of instances where oxygen increased and decreased were almost equal. However, the increases were somewhat larger, on the average, than the decreases (approximately 6% versus 3%). In tests with Dynatrol emulsions, increased oxygen concentration was observed in most cases.

3.8 Exhaust Gas Temperature

It is to be expected that the addition of water to the combustion process by any means whatsoever will result in lower exhaust gas temperatures. This expectation was, with a few exceptions, borne out in this test series involving emulsified fuel. In tests with the Daedalean emulsions lower exhaust temperatures were observed at every test condition. The range of the decreases was from less than 1% (negligible) to 6.3%. The overall average reduction was 3.8%. These data are presented in Table B-1 and Figures B-13 through B-15 of the Appendix, where it can be seen that the temperature decreased as the fuel-water content increased.

The corresponding exhaust temperature data from tests with the Dynatrol emulsions are presented in Table B-2 and Figures B-16 and B-17. There were fifteen instances where the temperature decreased and three cases where it increased. Two of these increases were so slight as to be considered negligible. The overall average decrease in temperature was 2%

and, in general, the largest decreases were obtained with the higher water percentages. However, the data are not as consistent in this regard as the data obtained with Daedalean emulsions.

3.9 Ignition Delay and Injection Timing

Another effect on engine performance which has been sometimes attributed to use of water-in-fuel emulsions is an increase in the ignition delay period (i.e., the time between the start of injection and the onset of combustion), which in turn necessitates an advance in injection timing in order to optimize power output under the given operating conditions. Some investigators report that under extreme conditions, such as when a high fuel-water content is being used, the ignition delay becomes so long that injection timing must be advanced by an amount sufficient to negate any decrease in NO_x that would ordinarily result from use of emulsified fuel. There is another consequence associated with this greatly advanced injection timing which bears upon the question of whether or not emulsified fuels are practical fuels for use in real-life diesel engines. Most laboratory research engines (including the CLR engine used in these tests) have an adjustment capability in their injection timing setting which is great enough to permit best power timing to be obtained even under conditions involving extremely long ignition delays. However, production engines usually have a much more limited range in the adjustment of injection timing; typically, 6° to 8° Crank Angle (CA) is the maximum injection advance that can be obtained without disassembling the pump in order to make an internal adjustment.

A limited analysis of the effect of the various emulsified fuels on ignition delay and best power timing (BPT) of the CLR engine was performed. The analysis was limited by the fact that the desired data must be obtained by visual analysis of the photograph of the oscilloscope traces showing injector needle lift, cylinder pressure, and crankshaft timing marks. With more than 350 tests performed, this analysis assumed formidable proportions. Hence, it was decided to analyze the photographic records for two or three tests at each condition (with baseline and emulsified fuels), and it is these data that are discussed here. In regard to the accuracy of this visual analysis of the traces, it should be understood that the photographic record can only be read to approximately ± 1° CA since this is the approximate width of the trace. Further, the point of injector needle lift is oftentimes not "clean" since the needle bounces or jiggles slightly as it starts to open. This situation introduces a certain amount of subjectivity into the visual analysis; it is estimated that this situation introduces another uncertainty into these data which is equal to 0.5 to 1.0° CA. It was therefore decided to interpret variations of 1.5° CA or less in a given value as constituting essentially no real change.

At the 1000 rpm test conditions, where fuel water contents up to 20 and 23.5% were used from the Daedalean and Dynatrol devices respectively,

ignition delay increased by a maximum of about 1.0° CA, a negligible change. It was not necessary to advance injection timing to compensate for this slight change; in fact, in all cases where emulsified fuels were used at this speed, the BPT was retarded slightly (approximately 1.0° to 1.5° CA) relative to the baseline BPT. This might be taken as indirect evidence of better (faster) mixing of fuel and air in the cylinder. The cause of this better mixing cannot be determined from the available data; candidates include the microexplosion phenomenon and changes in spray droplet size and spray penetration caused by the different viscosity and density of emulsified fuel.

At 2000 rpm and with water contents up to 20% (Daedalean) and 13.5% (Dynatrol), increases in ignition delay up to about 4.5° CA were observed, but only in a couple of instances. At most test conditions, the increase was on the order of 1.0° to 2.0°. Best power timing could again be retarded slightly or left essentially unchanged.

At 2500 rpm, where the Daedalean emulsion with 20% water was used, ignition delay was increased by 3.0° to 5.0° CA. With the higher value, it was necessary to advance injection timing by about two or three degrees to obtain best power.

In summary, it is encouraging that the use of these unstabilized emulsions did not produce drastic changes in the ignition delay and required BPT for the CLR test engine. Also, it is important to note that even when timing changes were required,they were well within the adjustment capabilities of most commercial injection systems. However, it must be emphasized that changes in ignition delay and BPT are characteristics of the injection system and combustion chamber designs used in a particular engine. Hence, while the results obtained here are encouraging, they cannot be extrapolated to other, real-life diesel engines. Actual testing with each engine operating on emulsified fuel will be required to determine whether or not similar results hold true.

3.10 Engine Operation, Lube Oil, and Wear

This section summarizes some qualitative and quantitative observations on the effect of emulsified fuel on the engine. First, engine operation was stable under all conditions and all fuel-water contents. The engine would idle smoothly on emulsion and, in one or two instances, the engine was started rather easily on emulsified fuel. The water content of the lube oil was measured by the Karl Fisher method at three points during the program. This water content was always low (less than 0.2%) and there was no increase in the values with operating time. At the end of the program the engine was disassembled and critical components were inspected visually. There was no sign of abnormal wear present for the rings, cylinder liner, crankshaft journal or crankshaft bearings. The lack of abnormal wear is further indication that the lube oil was not substantially degraded by use of these emulsions. The Bosch injector pump and nozzle performed normally throughout the program. However, neither one was disassembled for inspection.

The comments presented above are based upon 130 to 150 hours of engine operation on emulsified fuel. The results imply that short-term severe or catastrophic consequences did not occur in this particular engine. The question of whether or not the durability of modern production diesel engines would be substantially affected by use of emulsified fuels cannot and should not be inferred from these results.

blank
50

4. SUMMARY AND CONCLUSIONS

The primary objective of this program was to define the possible consequences (both favorable and adverse) associated with the use of unstabilized water-in-fuel emulsions in diesel engines. The emulsified fuel was produced on-line with the engine by two prototype emulsification devices. A single-cylinder, four-stroke cycle engine was operated using baseline fuel and emulsions containing from 2 to 23.5% water by volume. Effects associated with use of the emulsions were determined by making detailed measurements of fuel consumption, engine operating parameters, and exhaust emissions as the engine was operated through a test sequence involving back-to-back runs with baseline fuel and emulsified fuel. Four to six tests were conducted at each engine speed-load operating condition with both baseline and emulsified fuel, and the results of the fuel consumption measurement were statistically analyzed to determine if observed changes in this parameter could be stated at a 90% confidence level. Gaseous emissions data were obtained during just one set of test runs for each emulsion-water concentration.

The results of these tests are summarized in Table 4.1. The range of values and average value of the percentage change in each parameter is tabulated for emulsified fuel produced by each of the devices. The changes shown for indicated specific fuel consumption (ISFC) represent only those points where the change was statistically established. The average change in each parameter includes both positive and negative contributions in those cases where both were present. The only exception to this approach is explained in the footnote to the table. Established reductions in ISFC were obtained at 10 to 18 test conditions with each emulsification device. It is interesting to note that, even though the two devices produced emulsified fuel by differerent methods and their physical relationship to the engine was likewise completely different, the trends in the data obtained during the two test series are generally the same, with the principal difference being the magnitude of the change. No adverse effects on engine operating characteristics were encountered at any of the test conditions. No abnormal wear was in evidence when the engine was torn down and visually inspected at the end of the program.

It is concluded that the principal benefits associated with the use of emulsified diesel fuel in the test engine are reduced specific fuel consumption at some operating conditions, together with an overall reduction in exhaust smoke density and oxides of nitrogen (NO_x) concentration. Adverse effects found are sometimes substantial increases in concentration of unburned hydrocarbons and carbon monoxide. Inspection of the data indicates that optimization of the water content of the emulsion to the particular engine operating condition might enhance the benefits and minimize the drawbacks outlined here.

TABLE 4.1 . SUMMARY OF TEST RESULTS

Parameter	Daedalean Emulsions Δ% Range	Daedalean Emulsions Avg. Δ%	Dynatrol Emulsions Δ% Range	Dynatrol Emulsions Avg. Δ%
ISFC	0 to -5.1	-3.9	+2.5 to -3.9	-2.1*
NO_x Conc.	+7 to -58	-33	+26 to -59	-19
Smoke Density	-8 to -68	-40	-8 to -36	-17
UBHC Conc.	-10 to +65	+27	-17 to +131	+21
CO Conc.	-52 to +106	+25	-37 to +172	+23
CO_2 Conc.	+1.6 to -7.4	-3.0	+3.7 to -4.6	-0.3
O_2 Conc.	-6.5 to +13.6	+1.7	-8.8 to +17.8	-0.9
Exhaust Temp.	-0.7 to -6.3	-3.8	+2.3 to -6.9	-1.5
Ignition Delay	No Significant Increase			
Best Power Timing	No Significant Change			

*Average of reductions only; changes to -1.7% if 2.5% increase is included in average.

5. RECOMMENDATIONS

This program, like most, was a special-case situation involving a specific engine operating at specific test conditions. Therefore, the results should not be generalized to a variety of engines operating under different conditions. However, these preliminary results are encouraging and lead to the following recommendations:

1. A program similar to this one should be conducted with a multi-cylinder, modern production diesel engine, preferably of a type and configuration used by the U.S. Coast Guard. The engine should be substantially smaller than the large, medium-speed main propulsion diesels used in the larger classes of Coast Guard cutters. This approach will minimize the program cost and constitutes the next step in a logical progression to use emulsified fuel in the larger engines.

2. If emulsified fuel (with water content optimized to the range of engine operating conditions) produces overall favorable effects in the fuel consumption and emission characteristics of the multi-cylinder engine, the design and construction of a shipboard system to produce and handle emulsified fuel for an in-service Coast Guard engine should be undertaken. The final working prototype of this fuel system should be checked out in the laboratory in preparation for its installation onboard a Coast Guard vessel.

3. The emulsification system should be installed on a vessel powered by the same type of engine used in the laboratory evaluation. Following installation and checkout, the system should be subjected to a shipboard demonstration consisting of two parts. The first part should involve measurement of engine performance and emission characteristics to ascertain that the emulsified fuel produces essentially the same effects with the in-service engine as it did with the laboratory engine. The second part of this demonstration should involve a long-term (minimum of six to twelve months) field trial in order to assess the full consequences arising from use of emulsified fuel in the engine and to determine areas where the design and performance of the emulsification system can be improved.

APPENDIX A

Baseline Diesel Fuel Analysis

TABLE A-1. LABORATORY ANALYSIS OF TEST FUEL

Fuel Type: DF-2

Chemical Analysis, % by weight		
	Hydrogen	13.2
	Carbon	85.6
	Oxygen	<0.4
	Nitrogen	0.8
	Sulfur	0.07
Heat of Combustion (Lower) (BTU/LB) (Calculated)		19,000
Heat of Combustion (Higher) (BTU/LB)		19, 143
API Gravity (60° F)		37.2
Reid Vapor Pressure (PSI)		2.0
Cetane Number (Calculated)		50.73
Flash Point (° F)		146.0
Viscosity (Centistokes)		
	50° F	5.0
	100° F	2.54
	150° F	1.56
	210° F	1.07

Distillation:

%	°F
IBP	352
10	414
20	447
30	459
40	477
50	495
60	511
70	529
80	549
90	579
95	600
EP	634
% Recovery	99.5
% Residue	0.5
% Loss	0.0

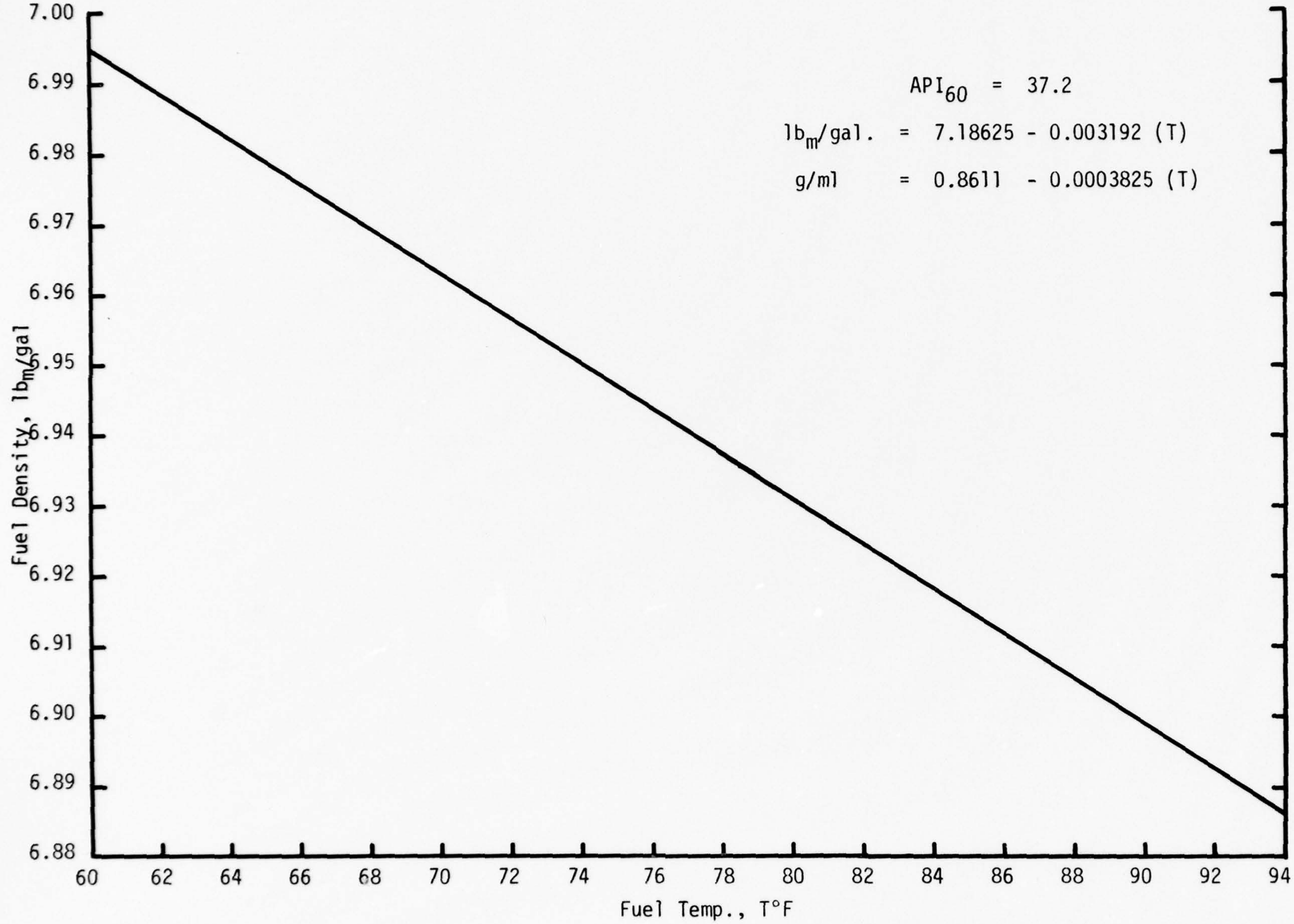


FIGURE A-1 - BASELINE DF-2 FUEL DENSITY AS A FUNCTION OF FUEL TEMPERATURE

APPENDIX B

Supplementary Engine Performance and Emissions Data

TABLE B-1. SUMMARY OF ENGINE PERFORMANCE, SMOKE, AND GASEOUS EMISSIONS DATA--DAEDALEAN EMULSIFIER

Engine Rev/Min	IMEP psi	H_2O in Fuel, Vol. %	ISFC, lbm/IHP-hr	% Change	Smoke Bosch No.	% Change	Exhaust Temp. °F	% Change	NOx, ppm	% Change	UBHC, ppmC	% Change	CO, ppm	% Change	CO2, %	% Change	O2, %	% Change
1000	60	0	.3197		0.3		449		635		1480		559		4.48		14.00	
	"	10	.3204	+0.2	0.7	+133.3	440	-2.0	575	-9.4	1824	+23.2	765	+36.9	4.55	+1.6	13.75	-1.8
	"	0	.3186		0.3		445		720		1296		623		4.55		14.75	
	"	20	.3257	+2.2	0.0	-100.0	429	-3.6	425	-41.0	1952	+50.6	1274	+104.5	4.34	-4.6	14.50	-1.7
	75	0	.3263		1.2		538		1170		1504		546		5.92		12.50	
	"	10	.3297	+1.0	1.1	-8.3	534	-0.7	825	-29.5	2000	+33.0	713	+30.6	5.84	-1.4	12.50	0
	"	0	.3187		1.5		536		895		1304		546		5.92		11.75	
	"	20	.3191	+0.1	0.7	-53.3	520	-3.0	570	-36.3	1984	+52.1	1123	+105.7	--	--	11.50	-2.1
	90	0	.3420		3.3		663		1125		904		804		7.54		10.25	
	"	10	.3470	+1.5	2.4	-27.3	641	-3.3	870	-22.7	1056	+16.8	1205	+49.9	7.45	-1.2	10.50	+2.4
	"	0	.3421		2.6		651		960		1456		1123		7.54		11.12	
	"	20	.3328	-2.7*	1.8	-30.8	611	-6.1	645	-32.8	2320	+59.3	1416	+26.1	7.18	-4.8	10.75	-3.3
2000	68	0	.2960		0.6		599		690		1184		546		5.29		13.75	
	"	10	.2939	-0.7	0.6	0	591	-1.3	525	-23.9	1368	+15.5	739	+35.3	5.14	-2.8	13.50	-1.8
	"	0	.2973		0.2		610		780		1136		598		5.37		13.13	
	"	15	.2879	-3.2*	0.0	-100.0	594	-2.6	460	-41.0	1600	+40.8	832	+47.5	5.14	-4.3	13.25	+0.9
	"	0	.2987		0.3		589		870		1120		533		5.37		12.37	
	"	20	.2916	-2.4*	0.0	-100.0	568	-3.6	400	-54.0	1200	+7.1	909	+70.5	5.22	-2.8	12.00	-3.0
	82	0	.3100		1.7		711		1380		1376		765		6.66		10.75	
	"	10	.3064	-1.2	0.7	-58.8	700	-1.5	1050	-23.9	1456	+5.8	765	0	6.75	+1.4	10.75	0
	"	0	.3111		1.7		735		1260		1296		675		7.09		11.12	
	"	15	.2986	-4.0*	0.3	-82.4	714	-2.9	530	-57.9	1392	+7.4	636	-5.8	6.92	-2.4	11.97	+7.6
	"	0	.3085		1.4		709		1330		1088		546		7.01		11.37	
	"	20	.2979	-3.4*	0.0	-100.0	664	-6.3	610	-55.8	1376	+26.5	856	+56.8	6.49	-7.4	10.63	-6.5
	96	0	.3346		4.7		862		1080		1096		1548		8.56		8.25	
	"	10	.3194	-4.5*	2.7	-42.6	839	-4.9	1155	+6.9	1360	+24.1	1068	-31.0	8.27	-3.4	9.13	+10.7
	"	0	.3252		4.4		896		1485		1712		2350		9.04		8.25	
	"	15	.3097	-4.8*	2.3	-47.7	855	-4.6	1275	-14.1	1704	+11.2	1315	-44.0	8.65	-4.3	8.75	+6.1
	"	0	.3207		4.4		866		1395		1032		1730		8.65		8.63	
	"	20	.3081	-3.9*	1.4	-68.2	814	-6.0	735	-47.3	1328	+28.7	1015	-41.3	8.46	-2.2	8.88	+2.9
2500	70	0	.3145		1.5		712		810		768		778		6.16		11.88	
	"	20	.3065	-2.5	0.0	-100.0	671	-5.8	450	-44.4	1264	+64.6	1163	+49.5	5.84	-5.2	12.25	+3.1
	86	0	.3239		2.8		862		1515		1040		1455		8.18		9.38	
	"	20	.3075	-5.1*	1.1	-60.7	819	-5.0	870	-42.6	1296	+24.6	1502	+3.2	7.99	-2.3	9.75	+3.9
	100	0	.3638		6.1		1099		1140		1568		6594		10.07		6.38	
	"	20	.3451	-5.1*	3.8	-37.7	1032	-6.1	825	-27.6	1408	-10.2	3175	-51.9	9.65	-4.2	7.25	+13.6

* Change Statistically Established at 90% Confidence Level

TABLE B-2. SUMMARY OF ENGINE PERFORMANCE, SMOKE, AND GASEOUS EMISSIONS DATA--DYNATROL EMULSIFIER

Engine Rev/Min	IMEP psi	H_2O in Fuel, Vol. %	ISFC, lbm/IHP-hr	% Change	Smoke Bosch No.	% Change	Exhaust Temp.°F	% Change	NOx, ppm	% Change	UBHC, ppmC	% Change	CO, ppm	% Change	CO2, %	% Change	O2, %	% Change
1000	60	0	.3156		0		442		690		1424		631		4.63		13.12	
	"	6.4	.3094	-2.0*	0	--	439	-0.7	500	-27.5	1888	+32.6	786	+24.6	4.48	-3.2	13.00	-0.9
	"	0	.3159		0.2		437		670		1640		616		6.49		11.50	
	"	14.4	.3150	-0.3	0	--	433	-0.9	450	-32.8	1760	+ 7.3	989	+60.6	6.33	-2.5	11.25	-2.2
	"	0	.3185		0.1		442		665		1520		631		4.77		14.25	
	"	23.5	.3266	+2.5*	0	--	424	-4.1	270	-59.4	1856	+22.1	1714	+171.6	4.55	-4.6	14.25	0
	75	0	.3222		0.7		534		1110		1280		586		5.92		12.50	
	"	5.2	.3184	-1.2*	0.6	-14.3	528	-1.1	915	-17.6	1520	+18.8	586	0	5.84	-1.4	12.37	-1.0
	"	0	.3267		1.3		532		870		1440		557		6.16		11.25	
	"	12.0	.3193	-2.3*	0.8	-38.5	525	-1.3	660	-24.1	1800	+25.0	616	+10.6	6.33	+2.8	13.25	+17.8
	"	0	.3255		1.1		529		795		1536		586		6.08		12.50	
	"	20.2	.3224	-1.0	0.5	-54.5	520	-1.7	440	-44.7	2192	+42.7	1097	+87.2	6.08	0	12.25	-2.0
	90	0	.3343		2.3		650		960		1280		852		7.36		9.75	
	"	4.3	.3328	-0.4	2.1	- 8.7	640	-1.5	860	-10.4	1344	+ 5.0	835	- 2.0	7.27	-1.2	9.75	0
	"	0	.3392		2.7		647		821		1720		868		7.81		10.75	
	"	10.0	.3327	-1.9	2.4	-11.1	634	-2.0	730	-11.0	2200	+27.9	936	+ 7.8	8.08	+3.5	10.50	-2.3
	"	0	.3365		3.0		656		880		1888		1079		7.72		10.25	
	"	17.0	.3321	-1.3*	2.7	-10.0	643	-2.0	520	-40.9	2016	+ 6.8	1439	+33.4	7.63	-1.2	10.25	0
2000	68	0	.2880		0.8		603		630		928		557		5.29		12.37	
	"	3.3	.2890	+0.3	1.4	+75.0	617	+2.3	540	-14.3	1856	+100.0	1061	+90.5	5.37	+1.5	11.87	-4.0
	"	0	.2920		0.8		606		655		1820		631		5.37		13.00	
	"	7.8	.2879	-1.4*	0.6	-25.0	608	+0.3	400	-38.9	1680	- 7.7	770	+22.0	5.37	0	12.25	-5.8
	"	0	.2879		1.0		595		500		1216		676		5.53		11.50	
	"	13.5	.2862	-0.6	0	--	584	-1.8	360	-28.0	1168	- 3.9	754	+11.5	5.37	-2.9	11.25	-2.2
	82	0	.2985		2.1		723		835		672		971		6.92		11.50	
	"	2.6	.2969	-0.5	1.6	-23.8	719	-0.6	930	+11.4	1552	+131.0	1550	+59.6	6.92	0	11.37	-1.1
	"	0	.3066		2.5		739		930		2000		1154		7.01		10.75	
	"	6.3	.3000	-2.2*	2.2	-12.0	740	+0.1	655	-29.6	1920	- 4.0	802	-30.5	7.27	+3.7	11.25	+4.7
	"	0	.3013		2.2		728		680		1312		1482		7.01		10.50	
	"	11.2	.2949	-2.1*	1.4	-36.4	716	-1.6	560	-17.6	1296	- 1.2	936	-36.8	7.18	+2.4	9.88	-5.9
	96	0	.3296		5.0		924		800		1728		2375		8.95		8.50	
	"	2.1	.3166	-3.9*	4.6	- 8.0	905	-2.1	825	+ 3.1	1664	- 3.7	1865	-21.5	8.85	-1.1	8.37	-1.5
	"	0	.3312		5.5		935		690		2980		3027		9.04		8.50	
	"	5.0	.3247	-2.0*	4.6	-16.4	914	-2.2	800	+15.9	3040	+ 2.0	1997	-34.0	8.95	-1.0	7.75	-8.8
	"	0	.3337		5.5		934		540		1936		4362		9.04		8.25	
	"	8.9	.3236	-3.0*	4.0	-27.3	870	-6.9	680	+25.9	1600	-17.4	2772	-36.7	8.95	-1.0	8.12	-1.6

* Change Statistically Established at 90% Confidence Level

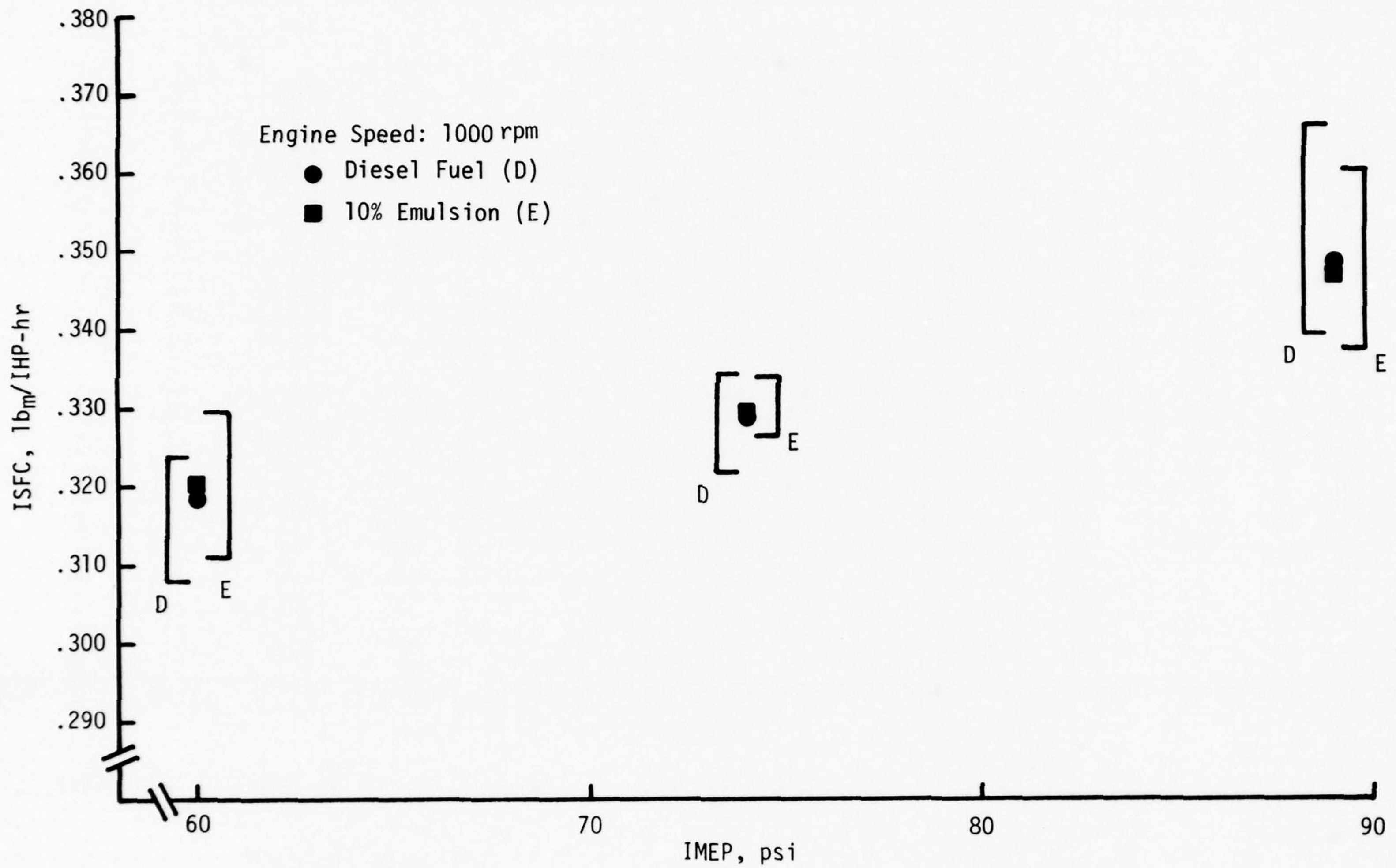


FIGURE B-1 - EFFECT OF 10% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

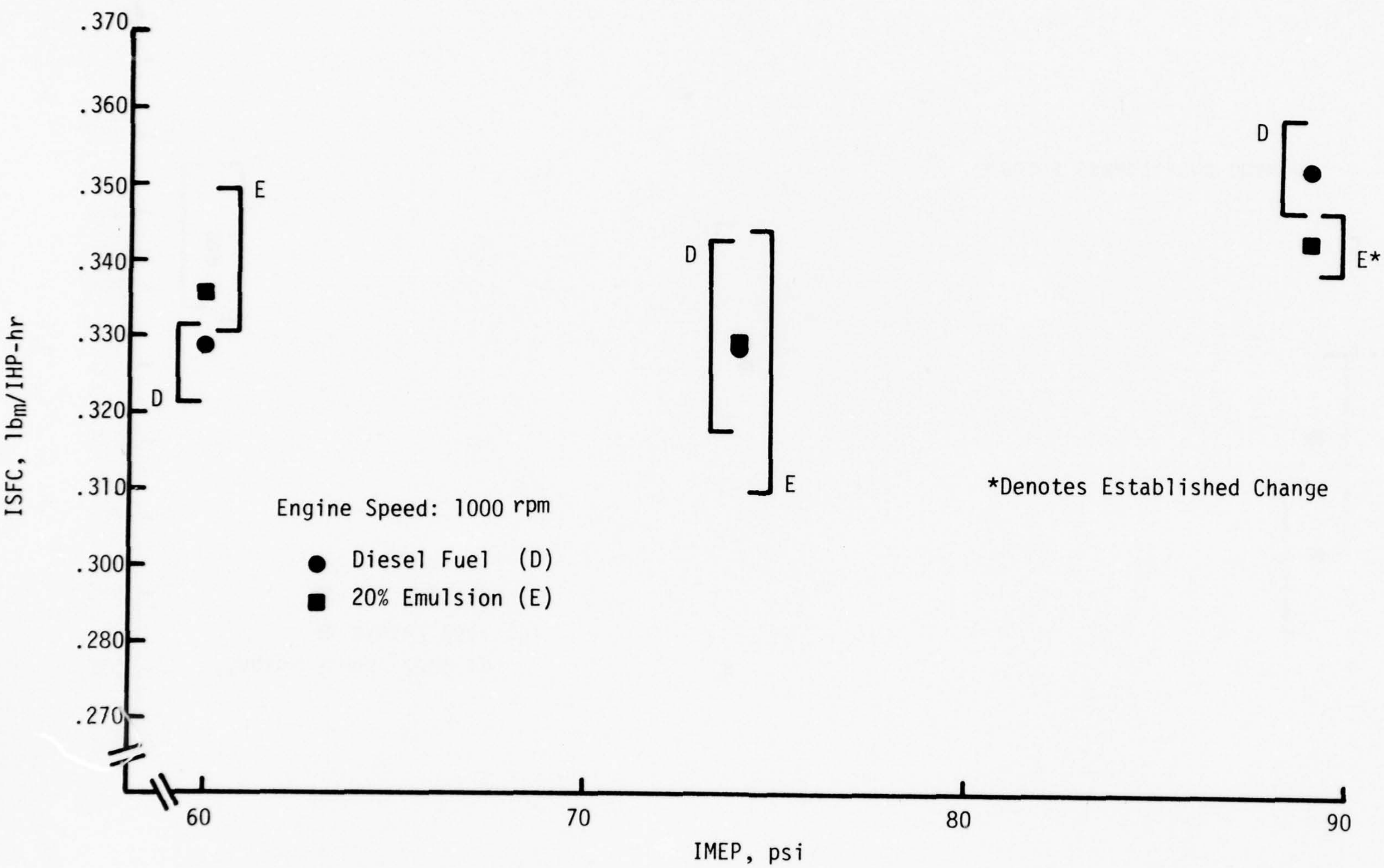


FIGURE B-2 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

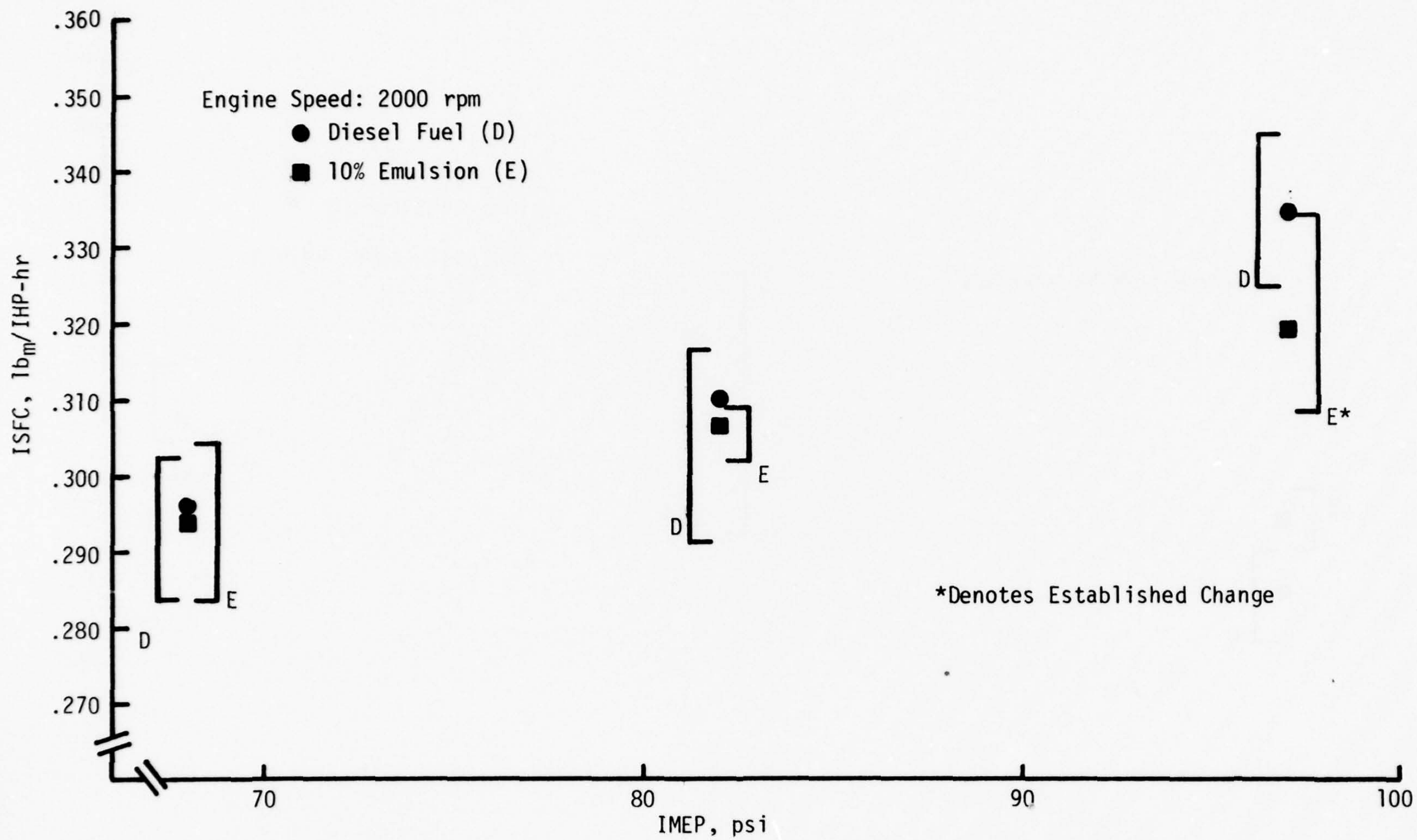


FIGURE B-3 - EFFECT OF 10% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

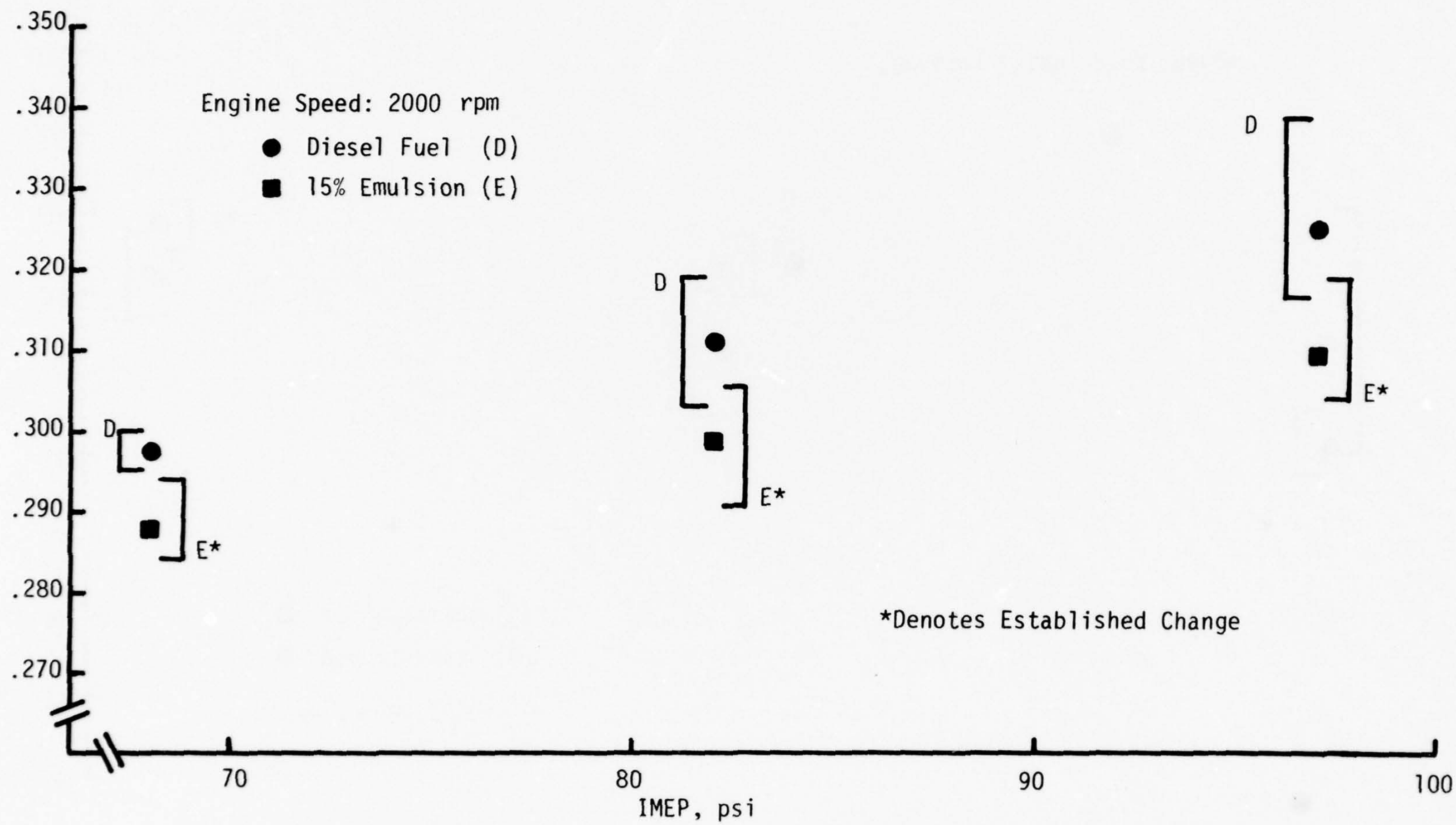


FIGURE B-4 - EFFECT OF 15% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

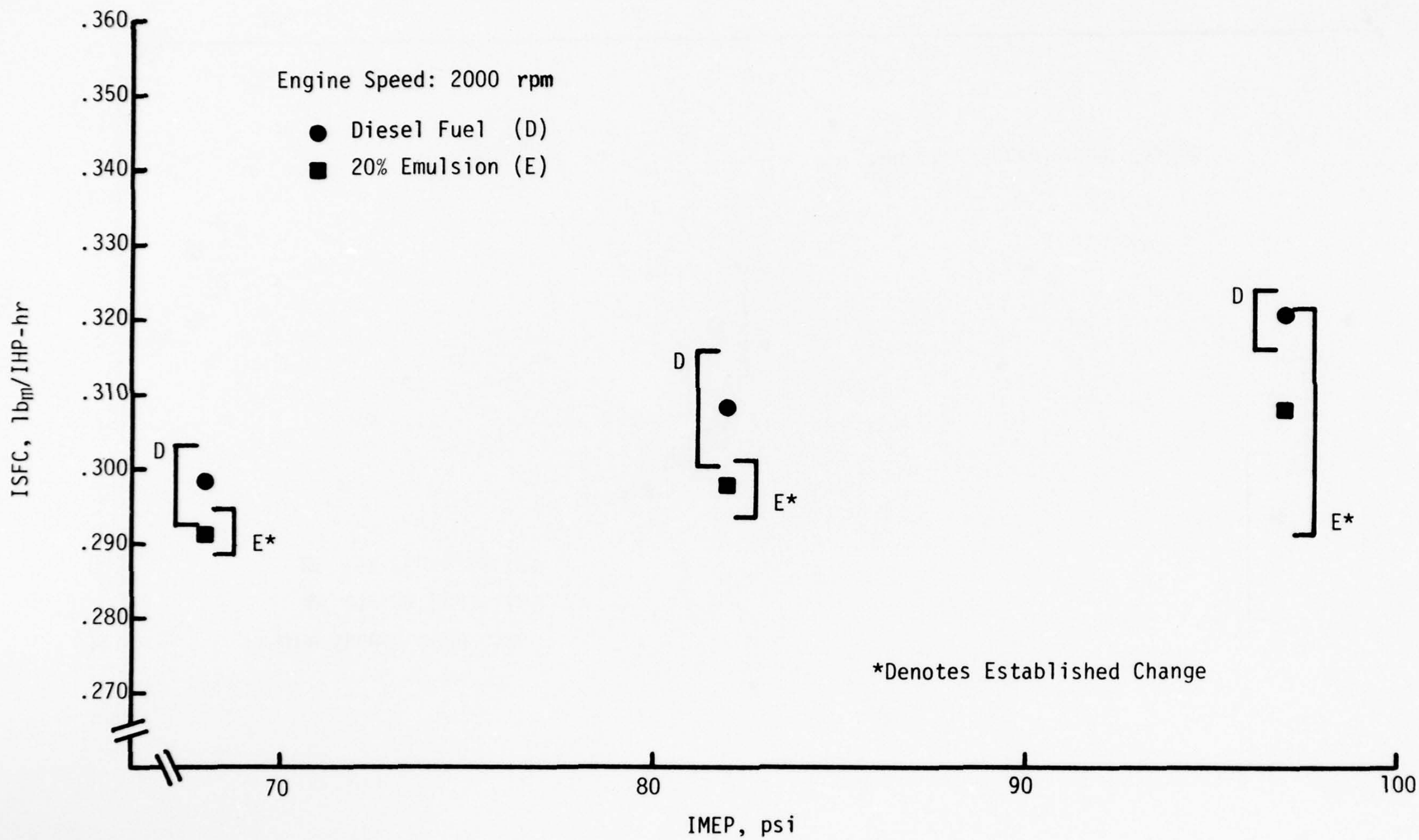


FIGURE B-5 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

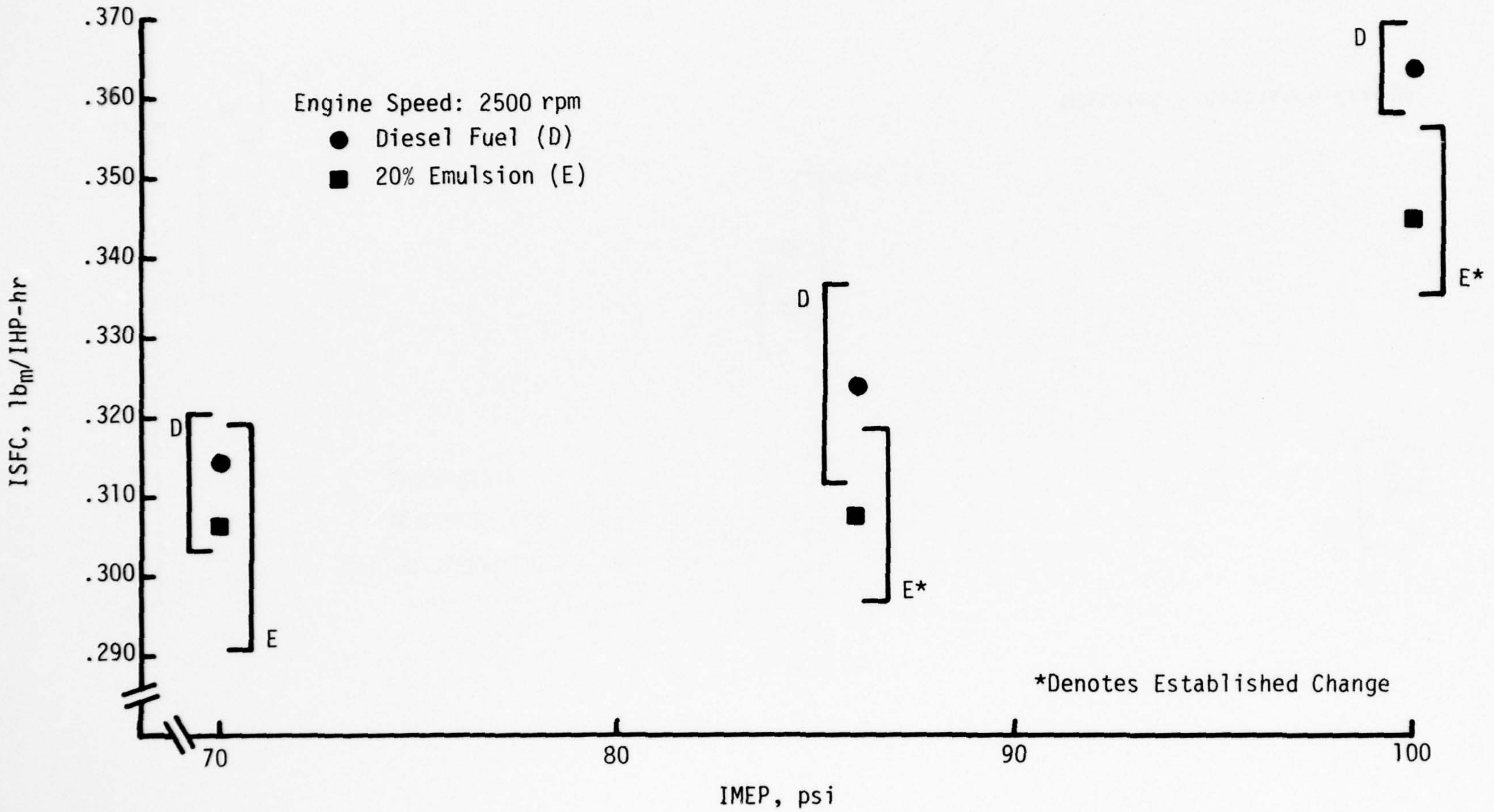


FIGURE B-6 - EFFECT OF 20% WATER-IN-FUEL EMULSION ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

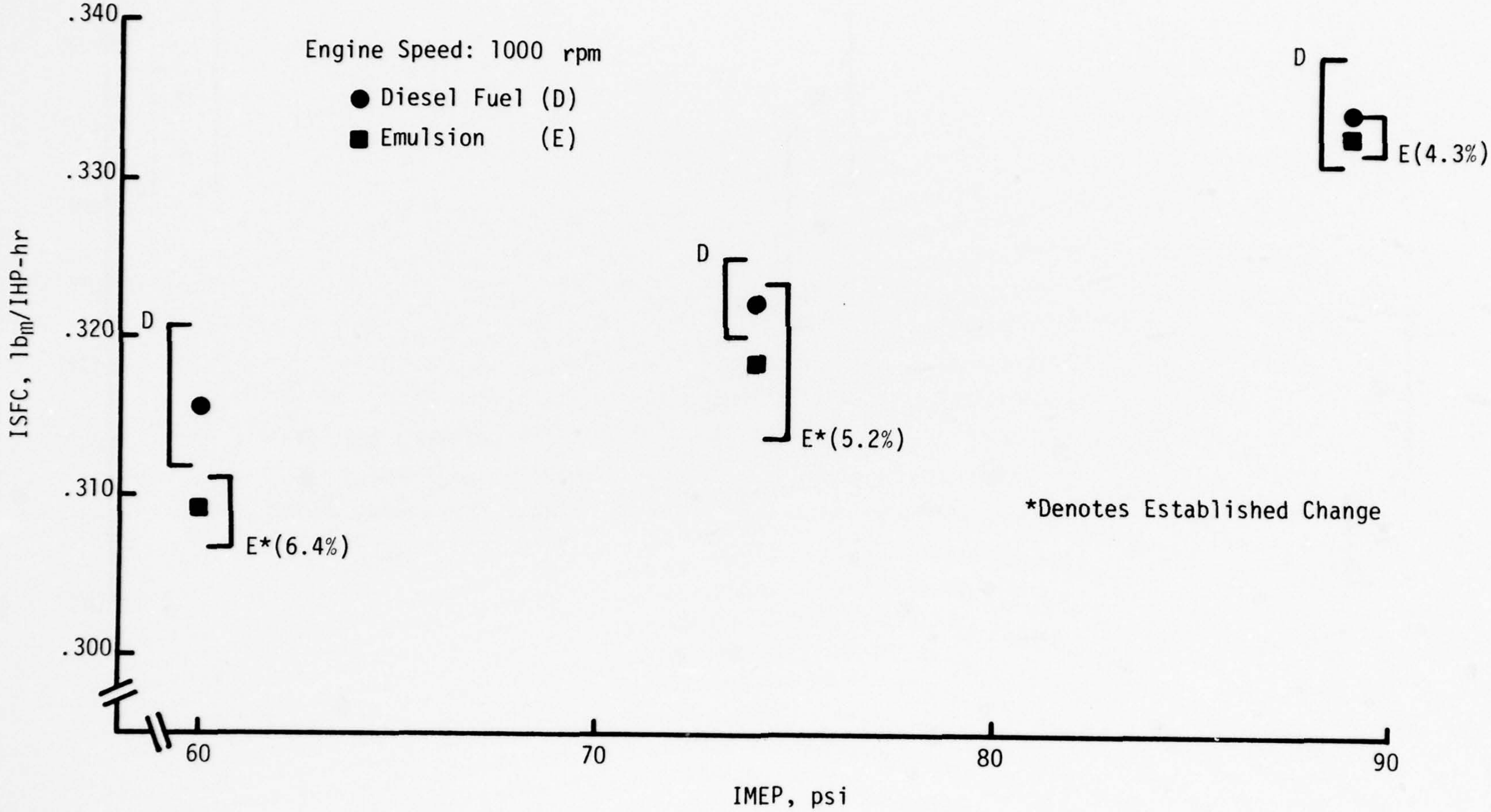


FIGURE B-7 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

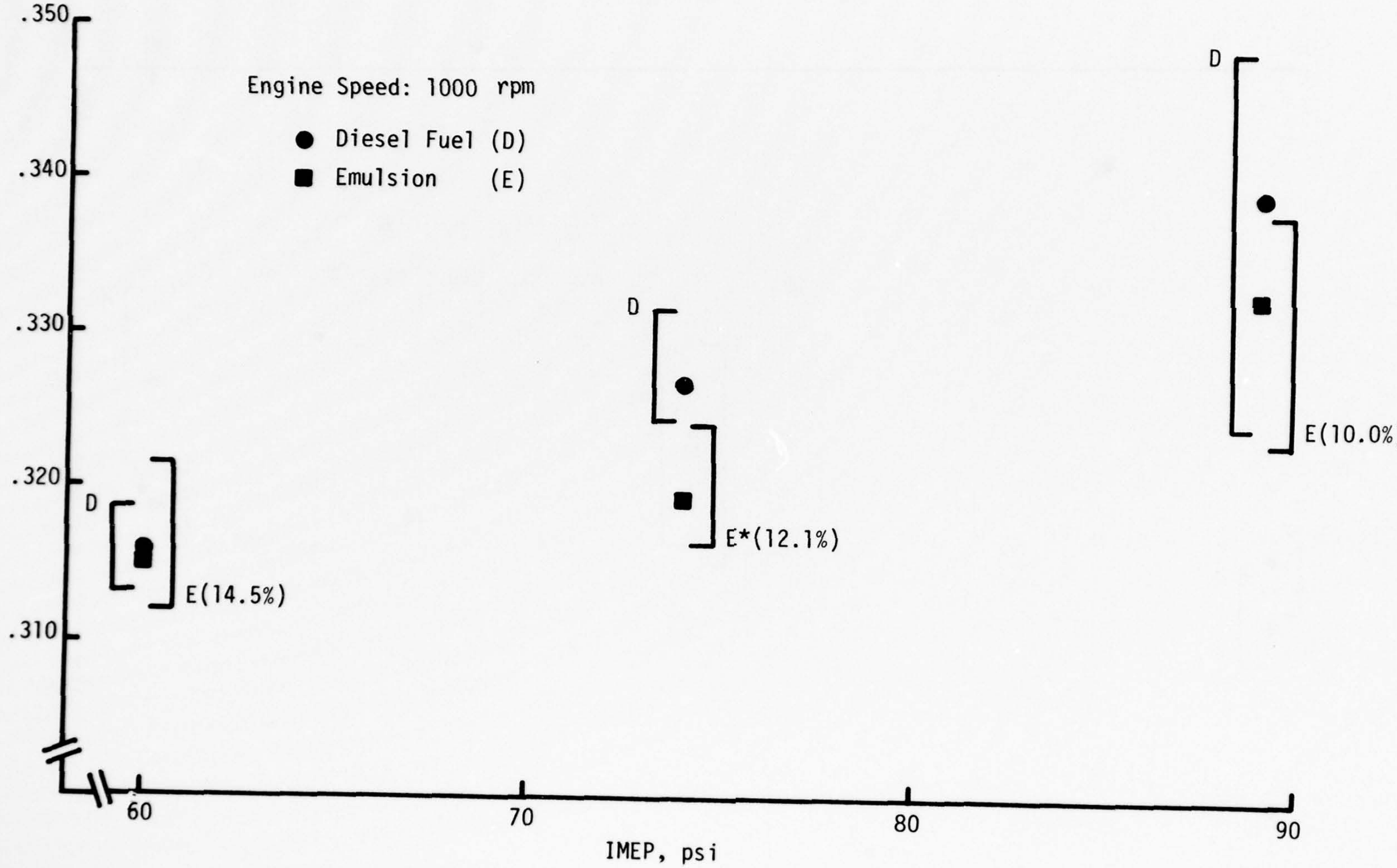


FIGURE B-8 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

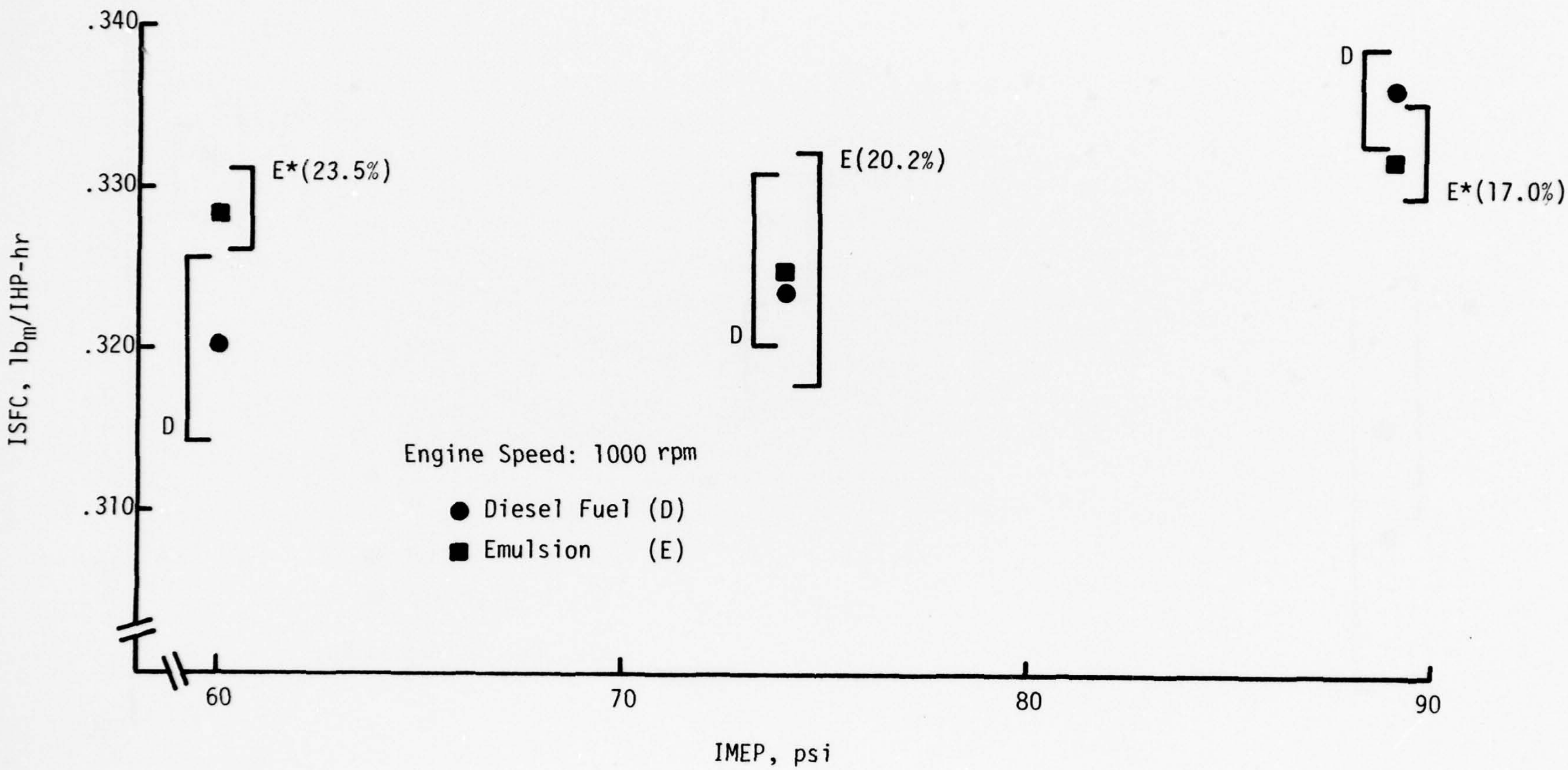


FIGURE B-9 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 1000 REV/MIN--DYNATROL EMULSIFIER

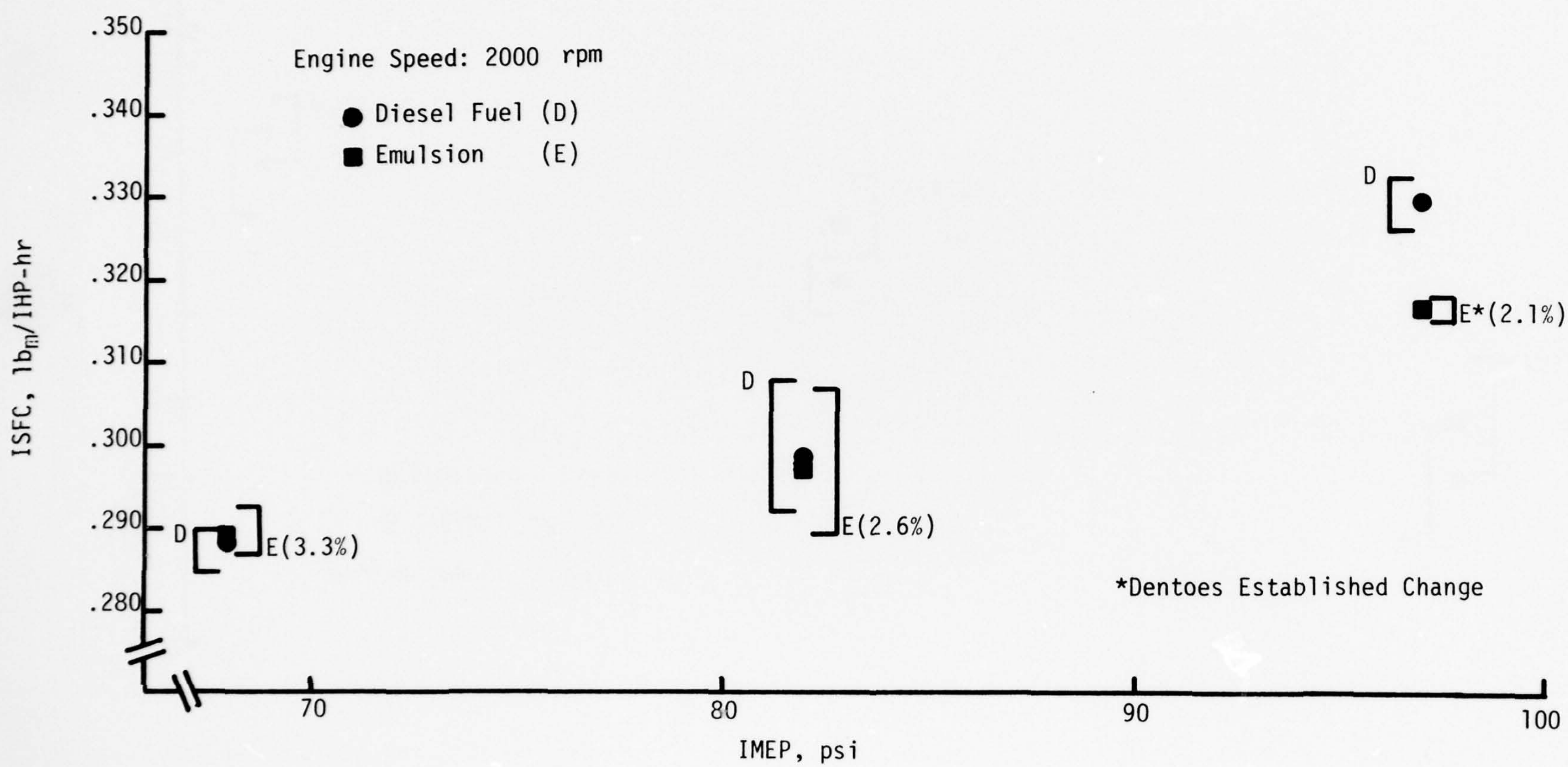


FIGURE B-10 - EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DYNATROL EMULSIFIER

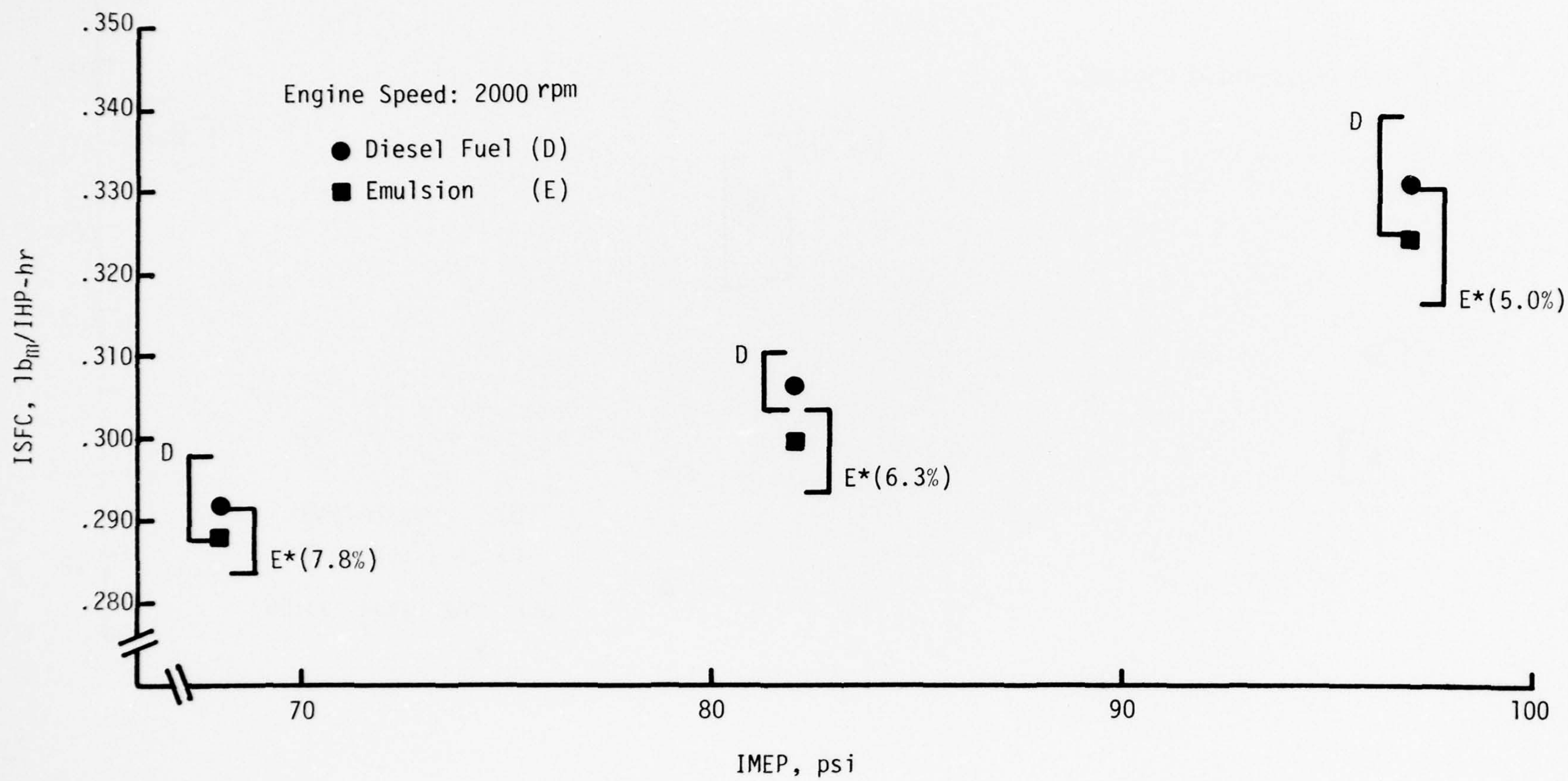


FIGURE B-11-EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DYNATROL EMULSIFIER

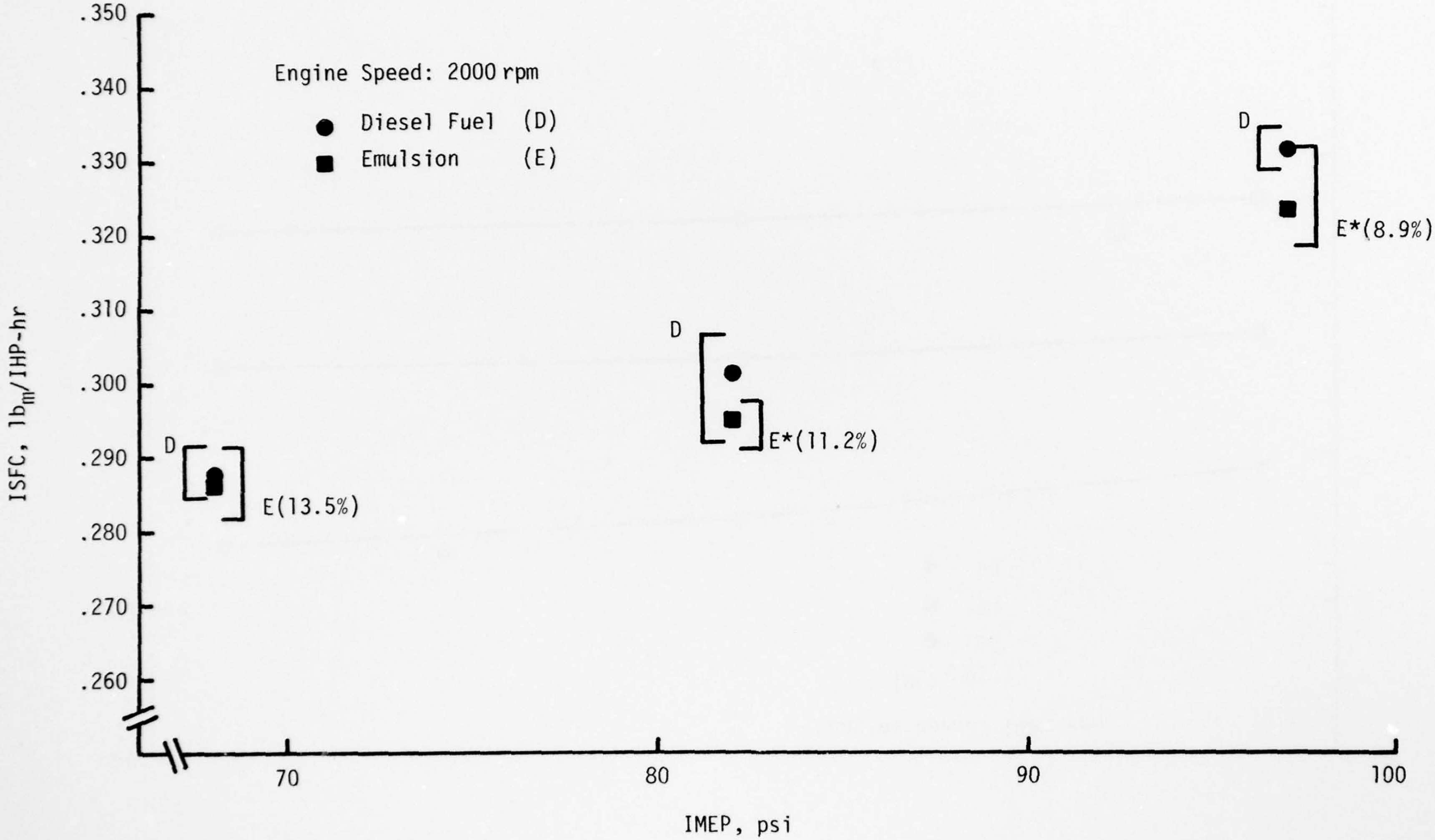


FIGURE B-12 -EFFECT OF EMULSIFIED FUEL ON ENGINE SPECIFIC FUEL CONSUMPTION AT 2000 REV/MIN--DYNATROL EMULSIFIER

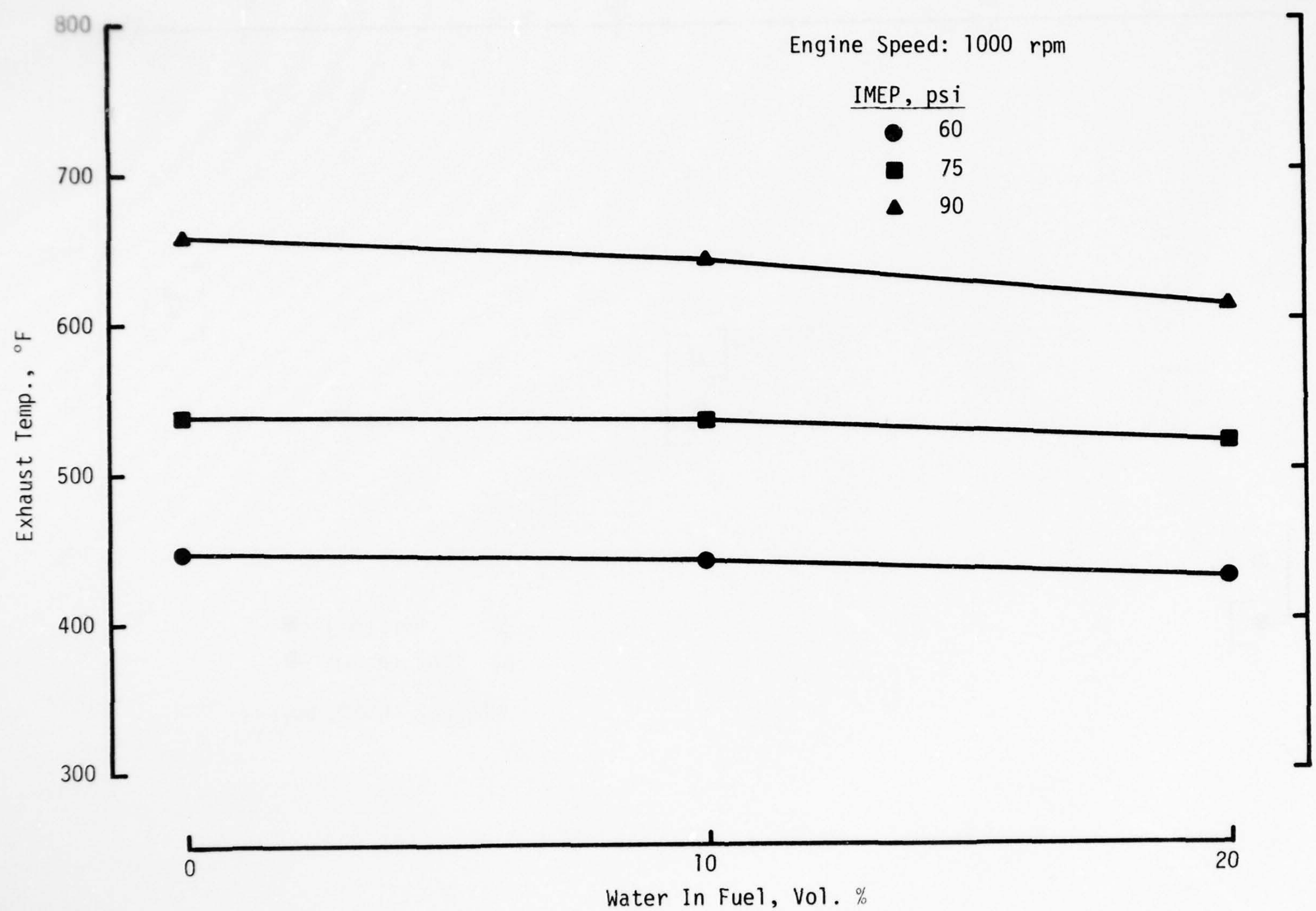


FIGURE B-13 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE AT 1000 REV/MIN--DAEDALEAN EMULSIFIER

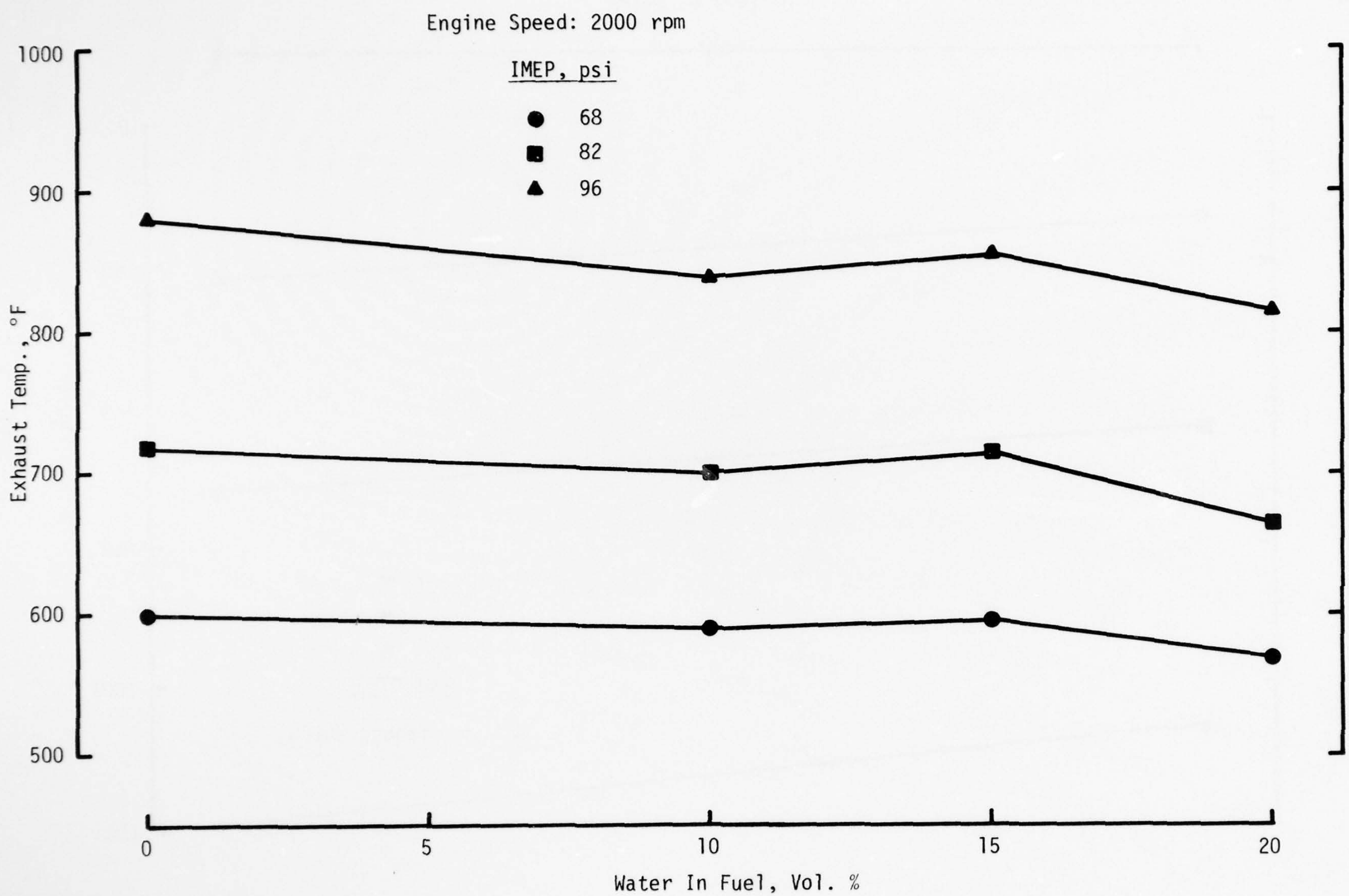


FIGURE B-14 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE AT 2000 REV/MIN--DAEDALEAN EMULSIFIER

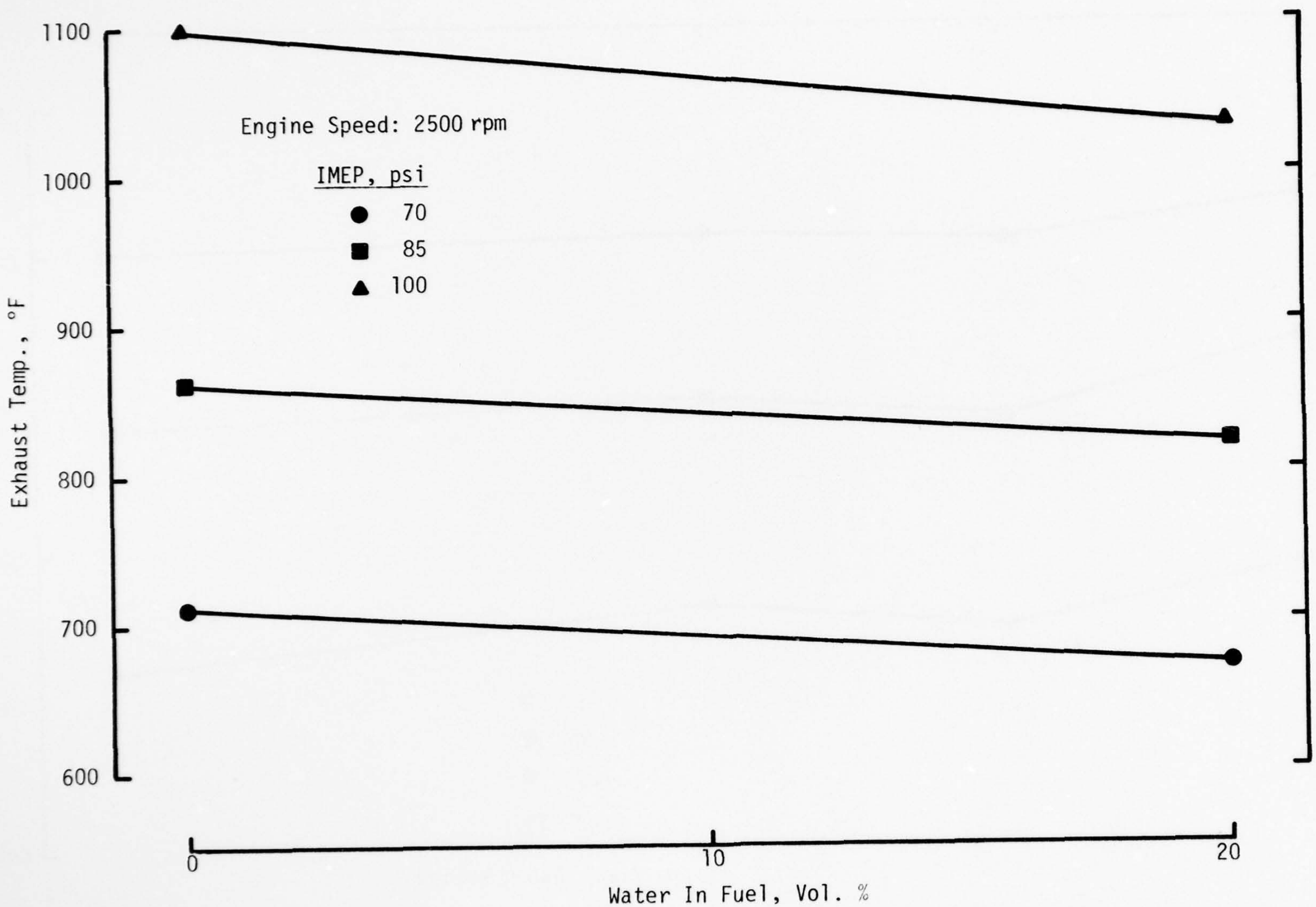


FIGURE B-15 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE AT 2500 REV/MIN--DAEDALEAN EMULSIFIER

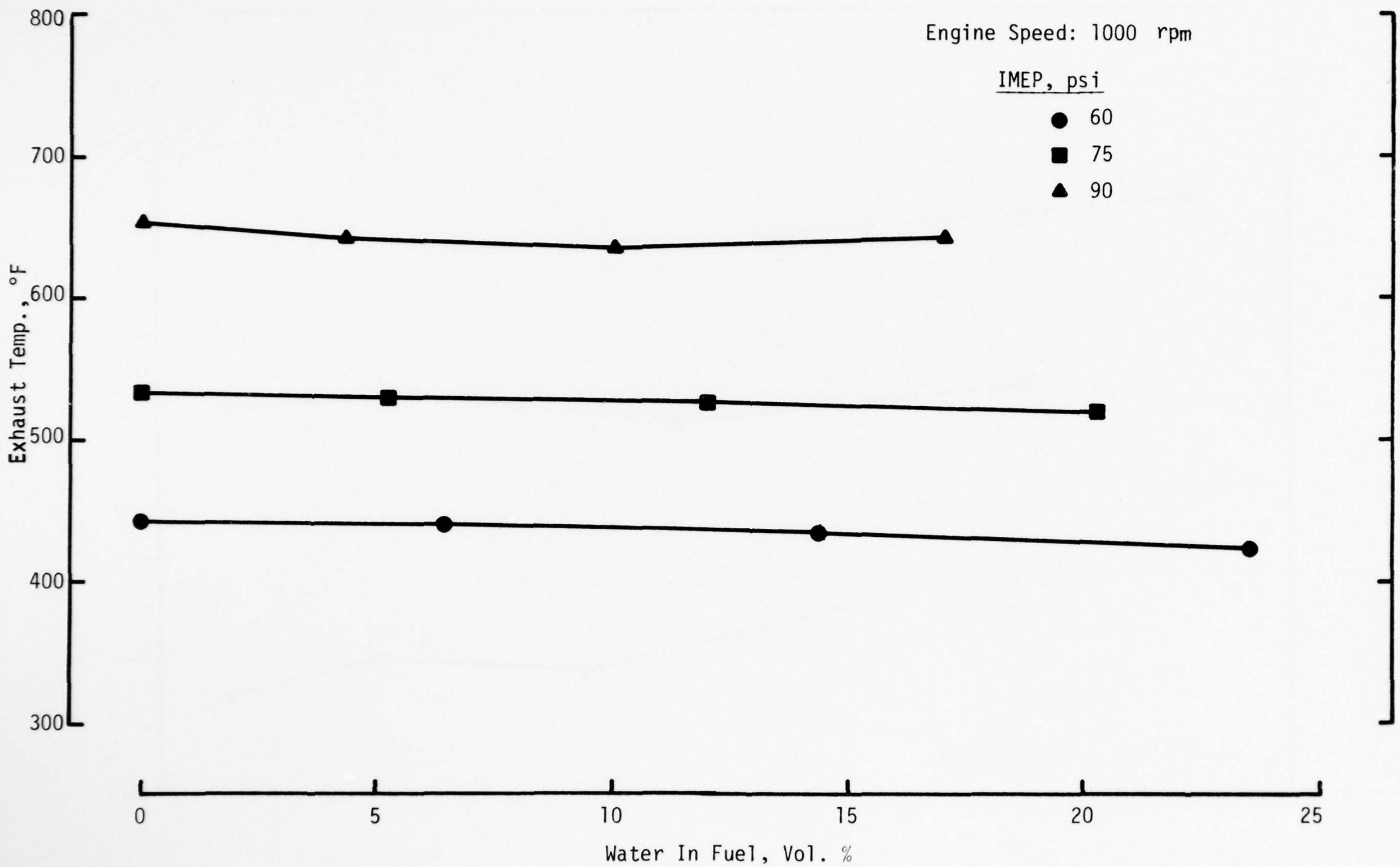


FIGURE B-16 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE
AT 1000 REV/MIN--DYNATROL EMULSIFIER

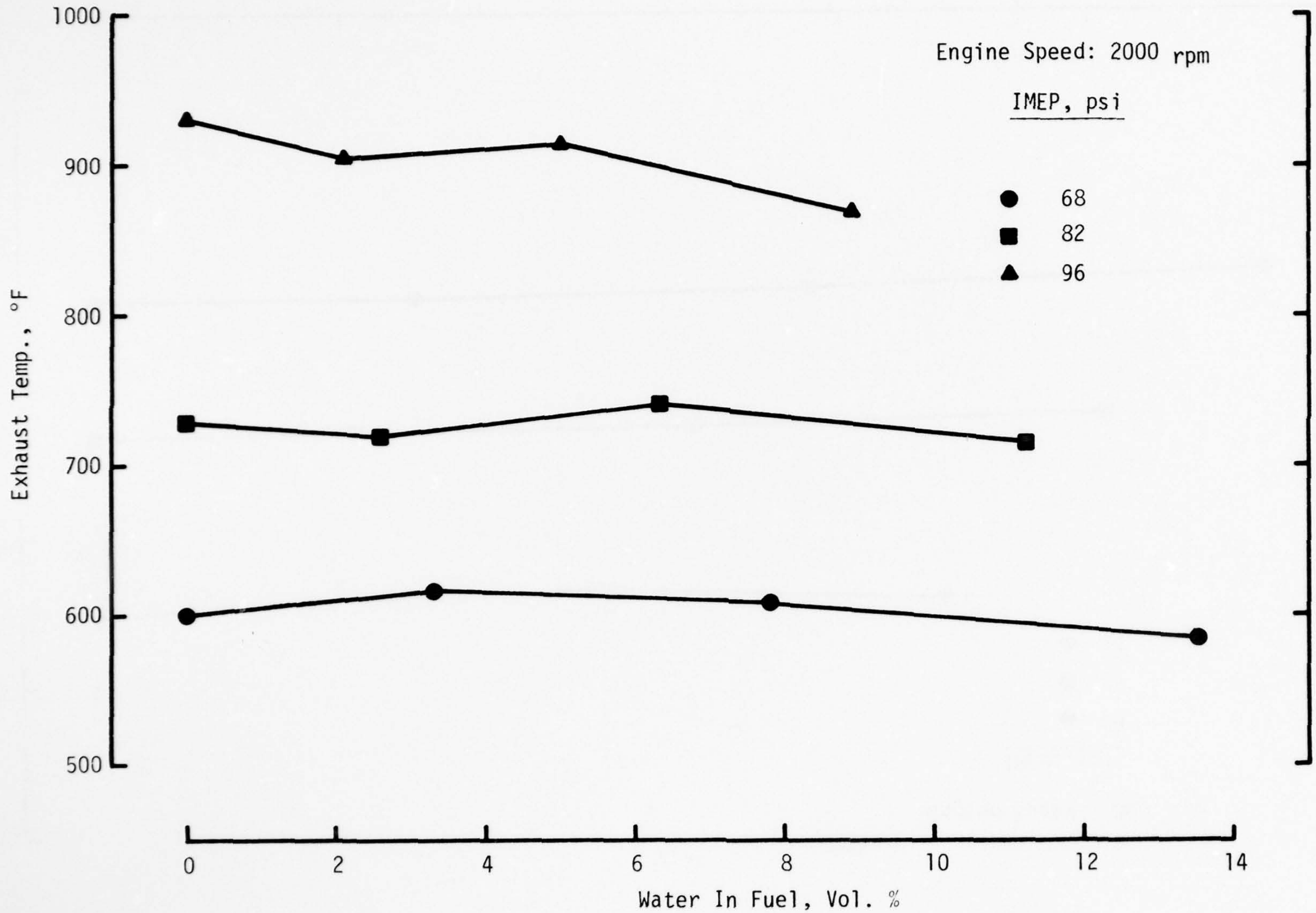


FIGURE B-17 - EFFECT OF EMULSIFIED FUEL WATER CONTENT ON EXHAUST TEMPERATURE AT 2000 REV/MIN--DYNATROL EMULSIFIER

APPENDIX C

REPORT OF INVENTIONS

The work performed under this contract produced no new inventions. However, a promising technique for improving the fuel economy and lowering the oxides of nitrogen and smoke emissions from diesel engines is described. This technique utilizes water emulsified into the diesel fuel to the engine. Although the tests reported on here were performed with a single-cylinder laboratory diesel engine, the methods described are applicable to diesel engines in general, though the same results may or may not be obtained.

REFERENCES

L. Moses, C. A., and C. W. Coon, Reduction of Exhaust Smoke from Gas - Turbine Engines by Using Fuel Emulsions, U.S. Fuels and Lubricants Research Laboratory, Southwest Research Institute, AFLRL Report No. 84 for the U.S. Naval Air Engineering Center.

2. Evaluation of Techniques for Improving Combustion Aboard Ship, Part 1--Boilers, Maritime Administration (MARAD) Report (no report number available at this time).

3. Owens, E. C., and B. R. Wright, Engine Performance and Fire-Safety Characteristics of Water-Containing Diesel Fuels, U.S. Army Fuels and Lubricants Research Laboratory, Southwest Research Institute, AFLRL Report No. 83 for the U.S. Army Mobility Equipment Research and Development Command, Energy and Water Resources Laboratory.

4. Murayama, F., et al, Experimental Reduction of NO_x, Smoke, and BSFC in a Diesel Engine Using Uniquely Produced Water (0 to 80%) to Fuel Emulsion, Society of Automotive Engineers (SAE) Paper 780224, 1978.

5. Spadaccini, L. J., and R. Pelmas, Evaluation of Oil/Water Emulsions for Application in Gas Turbine Engines, paper presented at Symposium on Evaporation-Combustion of Fuel Droplets.

6. Law, C. K., "A Model for the Combustion of Oil/Water Emulsion Droplets", published in Combustion Science and Technology, Vol. 17, pp. 29-38, 1977.

7. Owens and Wright, Engine Performance and Fire Safety Characteristics of Water-Containing Diesel Fuels.

8. Cornet, I., and W. E. Nero, "Emulsified Fuels in Compression Ignition Engines", published in Industrial and Engineering Chemistry, Vol 47, No. 10, pp. 2133-2141, 1955.

9. Valdmanis, E., and D. E. Wulfhorst, The Effects of Emulsified Fuels and Water Induction on Diesel Combustion, SAE Paper 700736, 1970.

10. Ibid.